UM1052
User manual

STM32F PMSM single/dual FOC SDK v4.2

Introduction

This manual describes the Motor Control Software Development Kit (STSW-STM32100) designed for and to be used with STM32F MCUs microcontrollers. The software library implements the Field Oriented Control (FOC) drive of 3-phase Permanent Magnet Synchronous Motors (PMSM), both Surface Mounted (SM-PMSM) and Internal (I-PMSM). The library exploit a new sensorless technique that, in conjunction with an I-PMSM motor, is able to extend the range of allowed speed to zero. This newest sensorless algorithm take benefit of the motor structure in order to detect the rotor angular position even when the motor is at low speed or still. In this user manual we will refer to this technique as "High Frequency Injection" also called HFI. This new algorithm take benefit of the floating point unit of STM32F30x and STM32F4 series.

The STM32F family of 32-bit Flash microcontrollers is based on the breakthrough ARM® Cortex®-M cores: the Cortex®-M0 for STM32F0, the Cortex®-M3 for STM32F1 and STM32F2, and the Cortex®-M4 for STM32F3 and STM32F4, specifically developed for embedded applications. These microcontrollers combine high performance with first-class peripherals that make them suitable for performing three-phase motors FOC.

The PMSM FOC library can be used to quickly evaluate ST microcontrollers and complete ST application platforms, and to save time when developing Motor Control algorithms to be run on ST microcontrollers. It is written in C language, and implements the core Motor Control algorithms as well as sensor reading/decoding algorithms and a sensorless algorithm for rotor position reconstruction. The library can be easily configured to make use of STM32F30x's embedded advanced analog peripheral set (fast comparators and Programmable Gain Amplifiers, PGA) for current sensing and protection, thus simplifying application board.

When deployed with STM32F103 (Flash memory from 256KBytes to 1MByte), STM32F2, STM32F303 or STM32F4 devices, the library allows simultaneous dual FOC of two different motors. The library can be customized to suit user application parameters (motor, sensors, power stage, control stage, pin-out assignment) and provides a ready-to-use Application Programming Interface (API). A user project has been implemented to demonstrate how to interact with the Motor Control API.

This project provides LCD and UART User Interface, thus representing a convenient real-time fine-tuning and remote control tool. A PC Graphical User Interface (GUI), the ST MC Workbench, allows a complete and easy customization of the PMSM FOC library. In a very short time the user can run a PMSM motor. A set of ready-to-use examples are provided to explain the usage of the motor control API and it's most common features.

Supported microcontrollers are listed in release note RN0085.

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1 Motor control library features

- "Motor profiler", a new algorithm able to auto-measure electromechanical Parameters of PMSM Motors (only for STM32F30x and STM32F4xx)
- "One touch tuning", a new algorithm that use a single parameter to set-up the speed controller according the type of load. Together with the "Motor profiler" can be enabled to achieve the setup and run of an unknown motor from the scratch (only for STM32F30x and STM32F4xx).
- "On-the-fly" sensorless startup, a new algorithm able to detect if the motor is running before the startup and skip the acceleration phase if not necessary. The motor is run in FOC from the begin without need to stop it before the start. This feature is particular useful for fan application (any STM32F supported).
- Single or simultaneous Dual PMSM FOC sensorless / sensored (Dual PMSM FOC only when running on STM32F103xx High-Density, STM32F103xx XL-Density or STM32F2xx or STM32F303xB/C or STM32F4xx)
- Speed feedback:
  - Sensorless:
    a) High Frequency Injection HFI (Patent pending) plus B-EMF State Observer, PLL rotor speed/angle computation from B-EMF, only for STM32F30x or STM32F4xx.
    b) B-EMF State Observer, PLL rotor speed/angle computation from B-EMF
    c) B-EMF State Observer, CORDIC rotor angle computation from B-EMF
  - 60° or 120° displaced Hall sensors decoding, rising/falling edge responsiveness
  - Quadrature incremental encoder
  - For each motor, dual simultaneous speed feedback processing
  - On-the-fly speed sensor switching capability
- Current sampling methods:
  - Two ICS (only when running on STM32F103xx or STM32F2xx or STM32F4xx)
  - Single, common DC-link shunt resistor (ST patented)
  - Three-shunt resistors placed on the bottom of the three inverter legs (only when running on STM32F103xx or STM32F2xx or STM32F302xB/C or STM32F30xB/C or STM32F4xx)
- Embedded analog peripherals (STM32F30x only)
  - PGA (Programmable Gain Amplifiers) for current sensing: support for three-shunt and single-shunt, internal and external gain
  - Comparators for over-current protection: support for three-shunt and single-shunt, internal and external threshold
  - Comparators for over-voltage protection: support for motor phases short-circuiting mode and free-wheeling mode, internal and external threshold
- FOC hardware acceleration(STM32F30x only)
  - ADC queue of context (ST patented architecture) support
  - CCM (Core Coupled Memory) RAM support
  - Advanced Timer structures for single shunt (ST patented) support
- Flux weakening algorithm to attain higher than rated motor speed (optional)

- Feed-Forward, high performance current regulation algorithm (optional)
- SVPWM generation:
  - Centered PWM pattern type
  - Adjustable PWM frequency
- Torque control mode, speed control mode; on-the-fly switching capability
- Brake strategies (optional):
  - Dissipative DC link brake resistor handling
  - Motor phases short-circuiting (with optional hardware over-current protection disabling)
  - Motor phases free-wheeling
- When running Dual FOC, any combination of the above-mentioned speed feedback, current sampling, control mode, optional algorithm
- Optimized I-PMSM and SM-PMSM drive
- Programmable speed ramps (parameters duration and final target)
- Programmable torque ramps (parameters duration and final target)
- Real-time fine tuning of:
  - PID regulators
  - Sensorless algorithm
  - Flux weakening algorithm
  - Start-up procedure (in case of sensorless)
- Fault conditions management:
  - Over-current
  - Over-voltage
  - Over-temperature
  - Speed feedback reliability error
  - FOC algorithm execution overrun
- Easy customization of options, pin-out assignments, CPU clock frequency through ST MC Workbench GUI
- C language code:
  - Compliant with MISRA-C 2004 rules
  - Conforms strictly with ISO/ANSI
  - Object-oriented programming architecture

User project and interface features

Two options are available:

- FreeRTOS-based user project (for STM32F103xx and STM32F2xx only)
- SysTick-timer-easy-scheduler-based user project

Available User Interface options (and combinations of them):

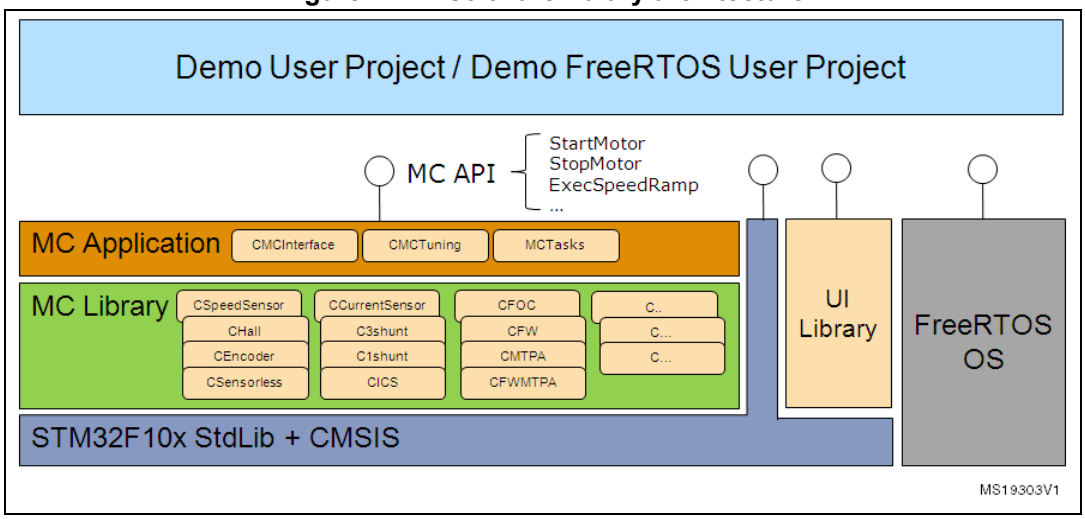
- Full LCD plus joystick
- Light LCD plus joystick
- Serial communication protocol bidirectional (compatible with ST MC Workbench GUI)
- Serial communication protocol fast unidirectional
- Drive system variables logging/displaying via:
  - SPI
  - DAC (DAC peripheral is not present in the STM32F103xx low or medium density; in this case, RC-filtered PWM signal option is available)

2 MC software development kit architecture

Figure 1 shows the system architecture. The Motor Control SDK has a four-layer structure:

- STM32Fxxx standard peripherals library and CMSIS library
- Motor control library
- Motor control application
- Demonstration user project

Figure 1. MC software library architecture



From the bottom layer upwards:

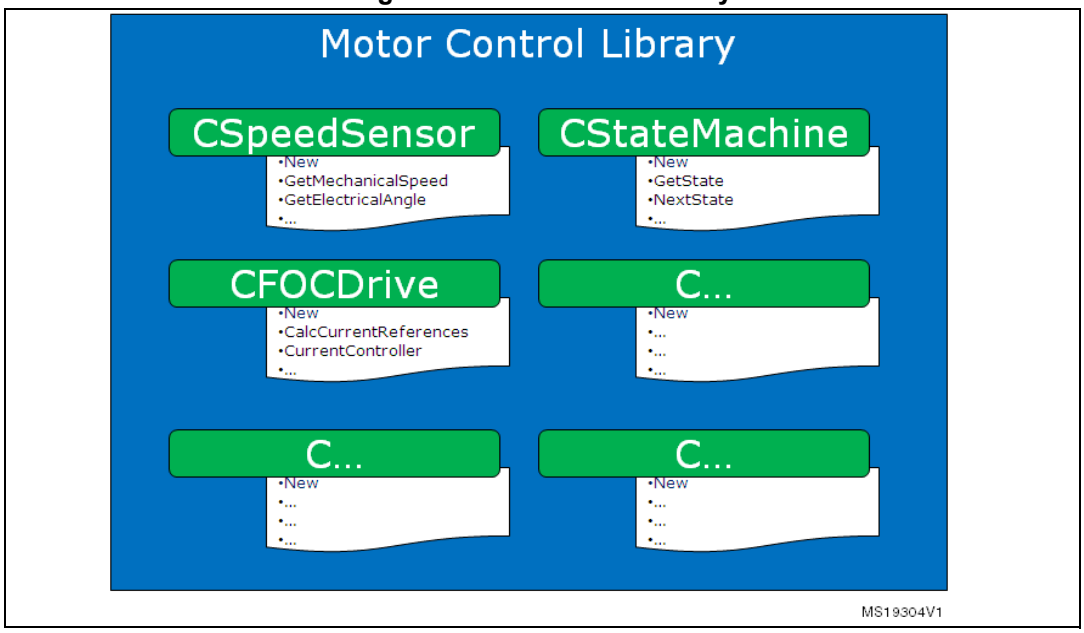
The STM32Fxxx standard peripherals library is an independent firmware package that contains a collection of routines, data structures and macros that cover the features of the STM32 peripherals. Version 3.5.0 of STM32F10x standard peripheral library is included in the MC SDK, version 1.0.0 is available for STM32F0x, STM32F2xx and STM32F4xx, version 1.0.1 is available for STM32F30x. The STM32Fxxx standard peripherals library is CMSIS and MISRA-C compliant. Visit www.st.com/stm32 for complete documentation.

The motor control library is a wide collection of classes that describe the functionality of elements involved in motor control (such as speed sensors, current sensors, algorithms). Each class has an interface, which is a list of methods applicable to objects of that class. *Figure 2* is a conceptual representation of the library.

Two distributions of the motor control library are available:

- Web distribution, available free of charge at www.st.com, where the motor control library is provided as a compiled .lib file.
- Confidential distribution, available free of charge on demand by contacting your nearest ST sales office or support team. Source class files are provided, except for ST protected IPs, which are furnished as compiled object files. Source files of protected IPs can also be provided free of charge to ST partners upon request. Contact your nearest ST office or support team for further information.

Figure 2. Motor control library



The motor control library uses the lower STM32Fxxx Standard Peripheral Library layer extensively for initializations and settings on peripherals. Direct access to STM32 peripheral registers is preferred when optimizations (in terms of execution speed or code size) are required. More information about the Motor Control Library, its classes and object oriented programming, can be found in the *Advanced developers guide for STM32F0x/F100xx/F103xx/STM32F2xx/F30x/F4xx MCUs PMSM single/dual FOC library (*UM1053).

The Motor Control Application (MCA) is an application that uses the motor control library in order to accomplish commands received from the user level. This set of commands is specified in its Application Programming Interface (API).

During its boot stage, the MCA creates the required controls in accordance with actual system parameters, defined in specific .h files that are generated by the ST MC Workbench GUI (or manually edited). It coordinates them continuously for the purpose of accomplishing received commands, by means of tasks of proper priority and periodicity. More information about the MCA can be found in *Section 10: MC application programming interface (API)*, and details on tasks and implemented algorithms in the *Advanced developers guide for STM32F0x/F100xx/F103xx/STM32F2xx/F30x/F4xx MCUs PMSM single/dual FOC library (*UM1053).

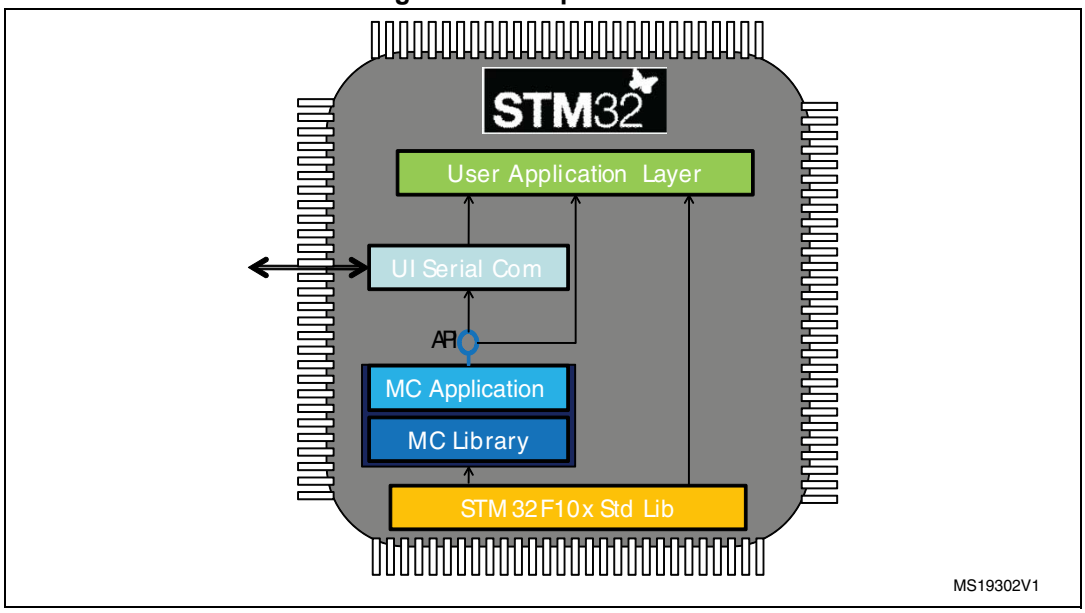
At the user level, a user project has been implemented to demonstrate how to interact with the MC API to successfully achieve the execution of commands. Depending on definable options, the user project can act as a Human Interface Device (using a joystick, buttons and LCD screens), as a command launcher through a serial communication protocol, as a data logging/displaying utility, or as a tuning tool.

Two versions of this user project are available (STM32F103xx and STM32F2xx only). One is based on FreeRTOS, the other is not. The demonstration user project can be dismantled and replaced by the user application layer, or quite easily integrated, as shown in *Figure 3*. The user application layer uses the STM32Fxxx Standard Library for its own purposes and sends commands directly to the MC API while the serial communication interface, provided

in the demonstration user project, dispatches commands received from the outer world to the MC API.

More information about the modules integrated with the demonstration user project, such as serial communication protocol, drive variables monitoring through DAC / SPI, HID (generically called 'UI library') and a description of LCD screens can be found in *Section 11: Full LCD user interface* and *Section 13: User Interface class overview*.

Figure 3. Example scenario



3 Documentation architecture

3.1 Where to find the information you need

Technical information about the MC SDK is organized by topic. The following is a list of the documents that are available and the subjects they cover:

- This manual (UM1052). This provides the following:
  - Features
  - Architecture
  - Workspace
  - Customization processes
  - Overview of algorithms implemented (FOC, current sensors, speed sensors, embedded analog topologies supported)
  - MC API
  - Demonstrative user project
  - Demonstrative LCD user interface
  - Demonstrative serial communication protocol
- *The User Manual* UM1053. This provides the following:
  - Object-oriented programming style used for developing the MC library
  - Description of classes that belong to the MC library
  - Interactions between classes
  - Description of tasks of the MCA
- MC library source documentation (Doxygen-compiled HTML file). This provides a full description of the public interface of each class of the MC library (methods, parameters required for object creation).
- MC Application source documentation (Doxygen-compiled HTML file). This provides a full description of the classes that make up the MC API.
- User Interface source documentation (Doxygen-compiled HTML file). This provides a full description of the classes that make up the UI Library.
- STM32F0xx, STM32F10x, STM32F2xx, STM32F30x or STM32F4xx Standard Peripherals Library source documentation (doxygen compiled html file).
- ST MC Workbench GUI documentation. This is a field guide that describes the steps and parameters required to customize the library, as shown in the GUI.
- In-depth documentation about particular algorithms (sensorless position/speed detection, flux weakening, MTPA, feed-forward current regulation).

Please contact your nearest ST sales office or support team to obtain the documentation you are interested in if it was not already included in the software package you received or available on the ST web site (*www.st.com*).

3.2 Related documents

Available from www.arm.com

- Cortex™-M0 Technical Reference Manual, available from: *http://infocenter.arm.com/help/topic/com.arm.doc.ddi0432c/DDI0432C_cortex_m0_r0p0_trm.pdf*
- Cortex™-M3 Technical Reference Manual, available from: *http://infocenter.arm.com/help/topic/com.arm.doc.ddi0337e/DDI0337E_cortex_m3_r1p1_trm.pdf*
- Cortex™-M4 Technical Reference Manual, available from: *http://infocenter.arm.com/help/topic/com.arm.doc.ddi0439c/DDI0439C_cortex_m4_r0p1_trm.pdf*

Available from www.st.com or your STMicroelectronics sales office

- STM32F030x datasheet
- STM32F051x datasheets
- STM32F100xx datasheet
- STM32F103xx datasheet
- STM32F20x and STM32F21x datasheets
- STM32F40x and STM32F41x datasheets
- STM32F051x reference manual (RM0091)
- STM32F100xx reference manual (RM0041)
- STM32F103xx reference manual (RM0008)
- STM32F20x and STM32F21x reference manual (RM0033)
- STM32F40x and STM32F41x reference manual (RM0090)
- STM32F103xx AC induction motor IFOC software library V2.0 (UM0483)
- STM32 and STM8 Flash Loader demonstrator (UM0462)
- STM32F302xB/C datasheet
- STM32F302x6/8 datasheet
- STM32F303xB/C datasheet
- STM32F30x reference manual (RM316)

4 Overview of the FOC and other implemented algorithms

4.1 Motor profiler and One Touch Tuning

The "Motor profiler" (also called "Self-commissioning") is a new algorithm able to auto-measure the electrical parameters of PMSM motors.

The "One touch tuning" is a new algorithm that use a single parameter to set-up the speed controller according the type of load.

They can be enabled together to achieve the run of an unknown motor from the scratch in few minutes.

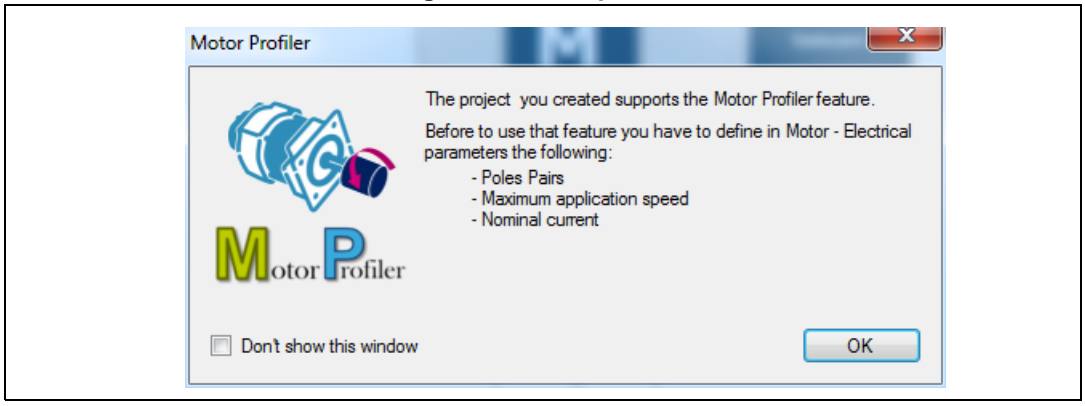
If enabled in the firmware this algorithms runs a set of electrical tests to determine the parameters required by the FOC and perform the auto tuning of the PI regulators (both current and speed). From now one we will refer with “Motor Profiler” both features.

The “Motor Profiler” algorithm will determine the following parameters:

- Stator resistance Rs
- Stator inductance Ls
- BEMF constant Ke
- KP and KI of speed controller
- Nominal speed of the motor

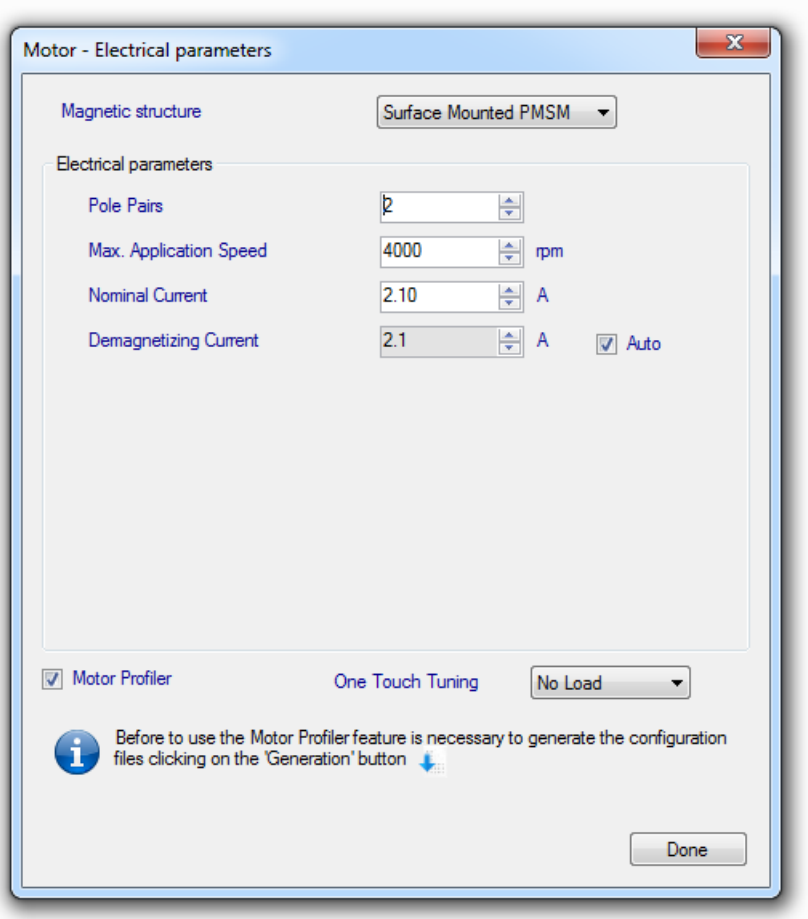
If the project supports the “Motor Profiler” feature, the dialog shown in *Figure 4* will appear.

Figure 4. Motor profiler


Motor Profiler
The project you created supports the Motor Profiler feature.
Before to use that feature you have to define in Motor - Electrical parameters the following:
- Poles Pairs
- Maximum application speed
- Nominal current
Motor Profiler
Don't show this window
OK

User can enable this functionality in any new Workbench project by checking the “Motor profiler” check box in the Motor – Electrical parameters dialog, like shown in *Figure 5*. When enabling “Motor profiler”, also enable the “One touch tuning” feature.

Figure 5. How to enable Motor Profiler



Enabling “Motor profiler”, the electrical parameters required by the FOC (Rs, Ls and Ke) will measured by the FW and the relative edit box disappear from the Motor – Electrical parameters dialog. Other parameters like pole pairs, maximum application speed and nominal current, will not be measured and must be insert by the user. In case of Internal PMSM is possible to change the magnetic structure setting and insert manually the Ld/Lq ratio.

To setup the “One touch tuning” is necessary to indicate the kind of load connected to the motor in a qualitative way:

- No load (small/medium sized motor without any load)
- Medium load (medium sized motor connected with load like pump of small fan)
- Big load (medium/high sized motor connected with full load of big fan)

This can be selected with the drop down menu “One touch tuning” in Motor – Electrical parameters dialog, like shown in *Figure 5*.

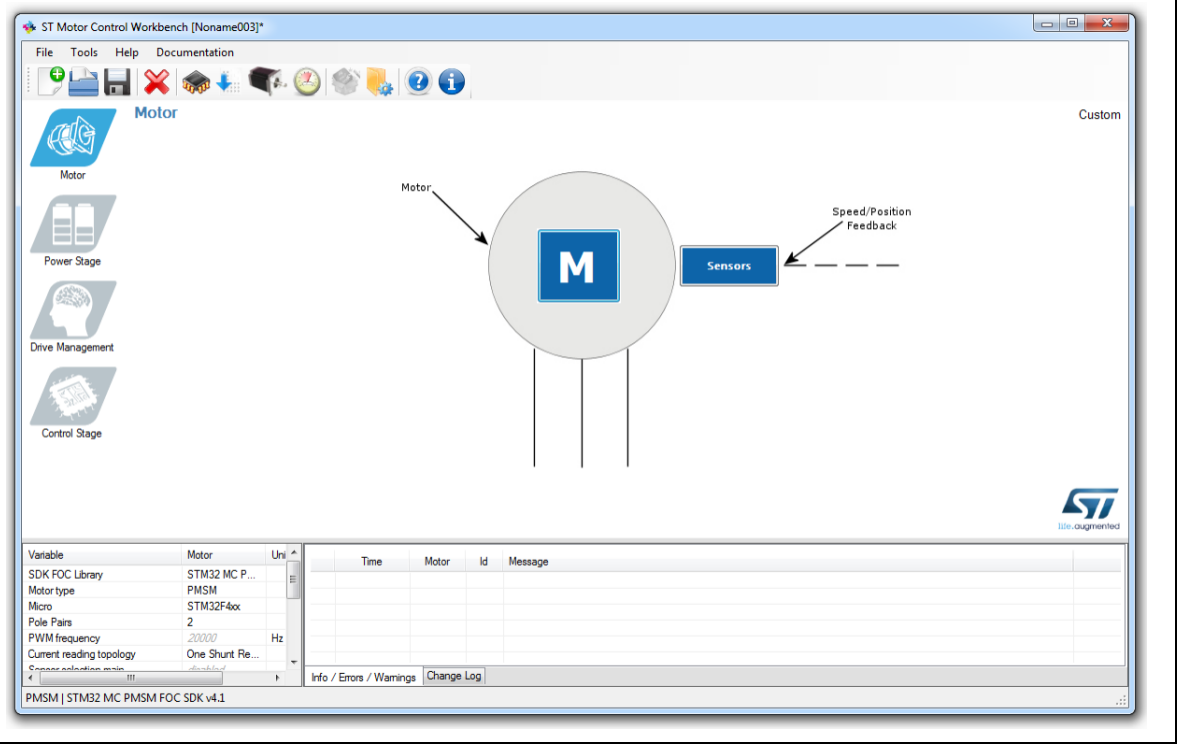
In this case, the pre-computed PI coefficient of current and speed regulators done by ST MC Workbench will not be used to drive the motor but they will be computed by the “Motor profiler” algorithm.

With the “Motor profiler” feature enabled and before to run it is necessary, as usual, to generate the .h files into the “SystemDriveParams” folder, compile and download the

executable into the microcontroller using a supported IDE (like IAR Embedded Workbench or Keil Microvision) as explained in the UM1052 – Chapter 9 – “Working environment”.

When the firmware is compiled and flashed into the micro is possible to use the ST MC Workbench real-time communication to send a “Motor profiler” command. To do this is necessary to Connect the control board with PC using RS232 (COM) null modem cable and press the Motor profiler button as shown in *Figure 6* starts the procedure.

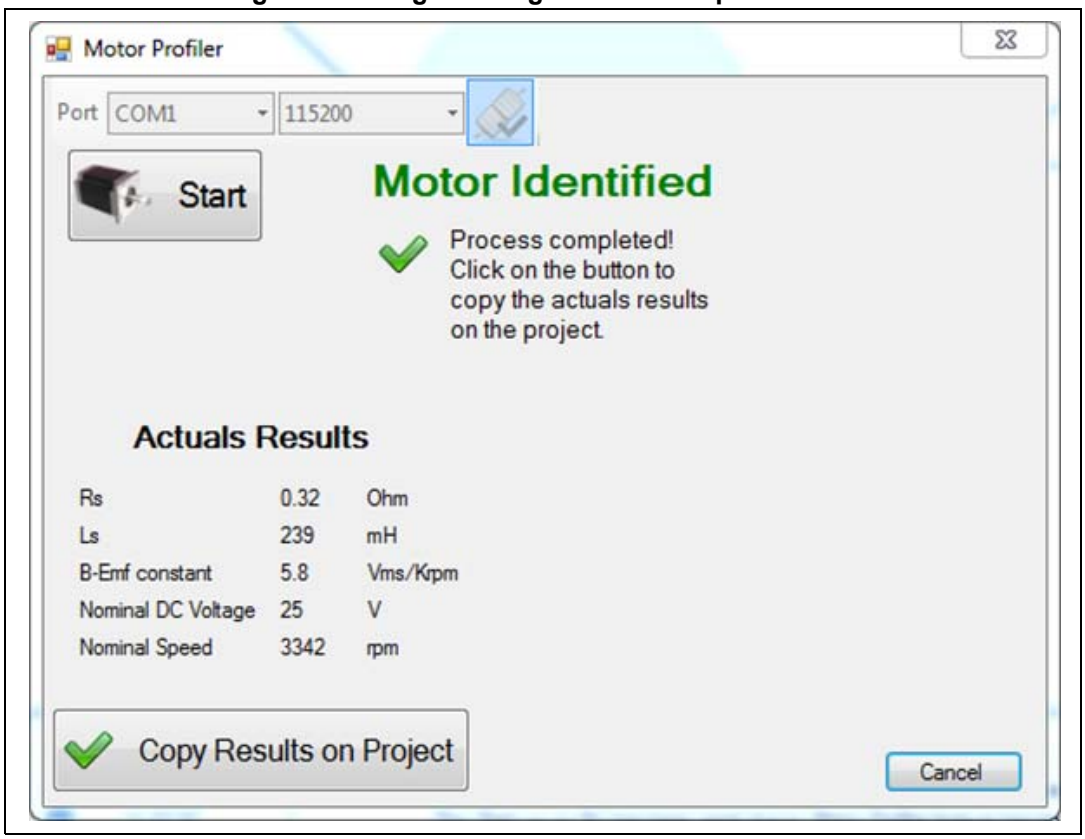
Figure 6. Send a “Motor profiler” command



A progress bar will show the status of the procedure and at the end the motor runs and, a dialog shows the measured parameters like in *Figure 7*.

If some errors occur during the procedure, the fault indication will be shown and the “Clear Fault” button can be pressed to reset the fault state.

Figure 7. Dialog showing the measure parameters



At the end of the procedure is also possible to import the measured parameter in the Workbench project pressing the “Copy Results on Project” button shown in *Figure 7*. Doing this the “Motor profiler” feature will be disabled and the firmware can be finalized removing the extra code required by that feature. The process of generating the .h file, compile and download, the finalized firmware is explained in explained in the UM1052 – Chapter 9 – “Working environment”.

Note: When Motor Profiler is enabled is possible to run the motor in standalone mode (no Workbench connection) using the LCD and Joystick feature (if present in the board). Pressing the Key button the Motor Profiler procedure will be executed before to start the motor. After one successfully identification of the motor the next startup will be executed using the parameters already measured without executing new Motor Profiler identification.

4.1.1 Restrictions

“Motor profiler” can be enabled only:

- For new Workbench projects (or WB example projects) if the selected power board support that feature.
- If a microcontroller of the STM32F3 or STM32F4 family is used in the WB project.
- In a single drive WB project.
- Using three shunts or single shunt current regulation.

When enabling “Motor profiler” is not possible to:

- enable the Flux Weakening
- enable the “On-the-fly” startup
- define a customized startup sequence
- use “Embedded PGA”

4.2 On-the-fly Sensorless startup

The "On-the-fly" sensorless startup is a new algorithm able to detect if the motor is running before the startup and skip the acceleration phase if not necessary. If the motor runs with a speed that is above the allowed threshold, the firmware apply the FOC from the beginning, without need to stop it and re-start. This feature is particular useful for fan application.

It is possible to enable this feature only when Sensor-less (Observer+PLL) or Sensor-less (Observer+Cordic) is selected in the Drive Management – Speed Position Feedback Management dialog.

To enable this feature check the “startup on Fly” check box in the Drive management – Start-up parameters dialog like shown in *Figure 8* and *Figure 9*.

Figure 8. Enabling "On-the-fly" start-up with Basic profile

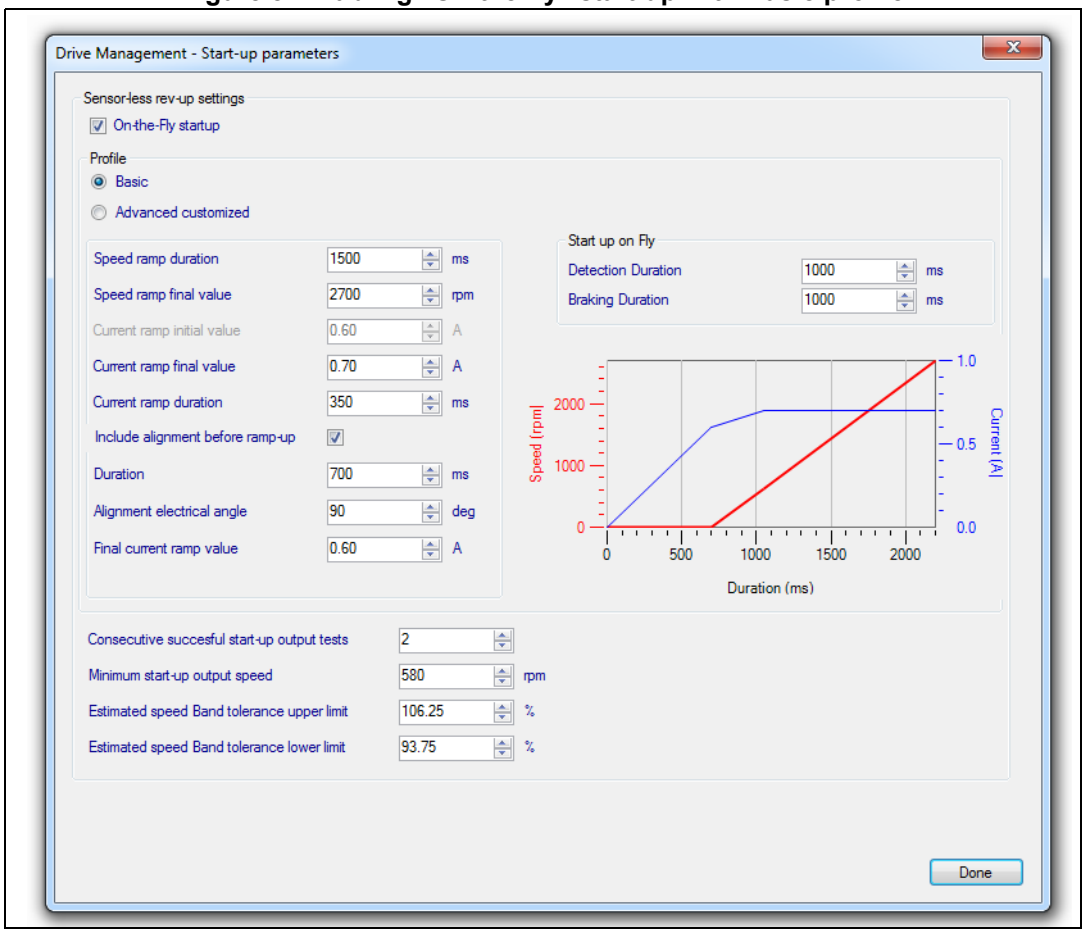
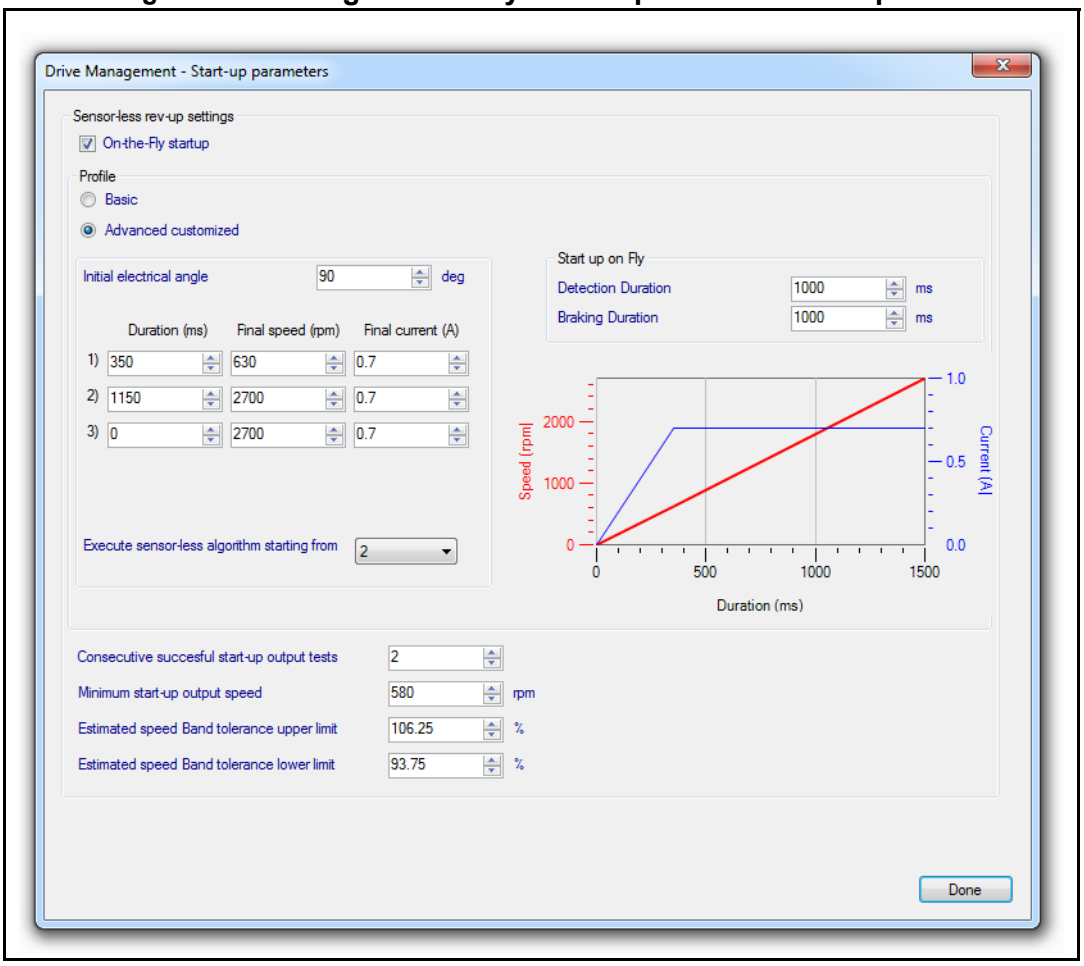

Drive Management - Start-up parameters
Sensor-less rev-up settings
On-the-Fly startup
Profile
Basic
Advanced customized
Speed ramp duration 1500 ms
Speed ramp final value 2700 rpm
Current ramp initial value 0.60 A
Current ramp final value 0.70 A
Current ramp duration 350 ms
Include alignment before ramp-up
Duration 700 ms
Alignment electrical angle 90 deg
Final current ramp value 0.60 A
Start up on Fly
Detection Duration 1000 ms
Braking Duration 1000 ms
Speed [rpm]
Current [A]
Duration (ms)
Consecutive succesful start-up output tests 2
Minimum start-up output speed 580 rpm
Estimated speed Band tolerance upper limit 106.25 %
Estimated speed Band tolerance lower limit 93.75 %
Done

Figure 9. Enabling "On-the-fly" start-up with Advanced profile



The speed threshold used to determine if is possible to skip the acceleration phase is the “Minimum startup-output speed” that represents the minimum speed for which the sensorless observer gives a reliable measurements. This can be select by the user according the nominal speed of the motor.

When enabling the “On-the-fly” startup two other parameter will appear in the dialog box:

- Detection duration
- Braking Duration

Both quantity are expressed in milliseconds and represents respectively:

- The duration of the “detection phase” of the OTF startup. Within this duration the reliability of the sensorless measurements are tested in order to validate the speed and run directly in FOC.
- The duration of the “braking phase” that is applied if the sensorless measurements doesn’t give reliable measurement during the “detection phase”. During the “braking phase” the motor is brake in order to stop it before the new acceleration.

Both, “Basic startup profile” and “Advanced startup profile”, can be used if the OTF startup is enabled. The two extra phases “detection phase” and “braking phase” are common of the two profiles. The startup profile can be set by the user to define the acceleration strategy if the speed of the motor is below the reliability threshold during the “detection phase”.

4.3 Introduction to the PMSM FOC drive

This software library is designed to achieve the high dynamic performance in AC permanent-magnet synchronous motor (PMSM) control offered by the well-established field oriented control (FOC) strategy.

With this approach, it can be stated that, by controlling the two currents i_{qs} and i_{ds}, which are mathematical transformations of the stator currents, it is possible to offer electromagnetic torque (T_e) regulation and, to some extent, flux weakening capability.

This resembles the favorable condition of a DC motor, where those roles are held by the armature and field currents.

Therefore, it is possible to say that FOC consists of controlling and orienting stator currents in phase and quadrature with the rotor flux. This definition makes it clear that a means of measuring stator currents and the rotor angle is needed.

Basic information on the algorithm structure (and then on the library functions) is represented in *Figure 10*.

- The i_{qs} and i_{ds} current references can be selected to perform electromagnetic torque and flux control.
- The space vector PWM block (SVPWM) implements an advanced modulation method that reduces current harmonics, thus optimizing DC bus exploitation.
- The current reading block allows the system to measure stator currents correctly, using either cheap shunt resistors or market-available isolated current Hall sensors (ICS).
- The rotor speed/position feedback block allows the system to handle Hall sensor or incremental encoder signals in order to correctly acquire the rotor angular velocity or position. Moreover, this firmware library provides sensorless detection of rotor speed/position.
- The PID-controller blocks implement proportional, integral and derivative feedback controllers (current regulation).
- The Clarke, Park, Reverse Park & Circle limitation blocks implement the mathematical transformations required by FOC.

Figure 10. Basic FOC algorithm structure, torque control

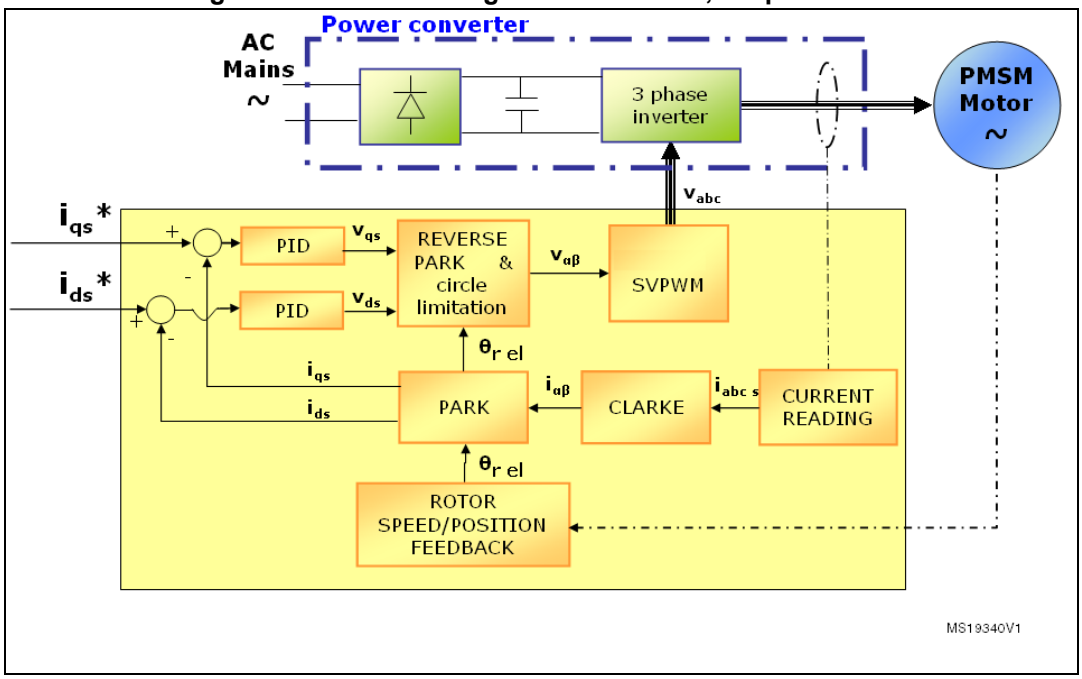


Figure 11. Speed control loop

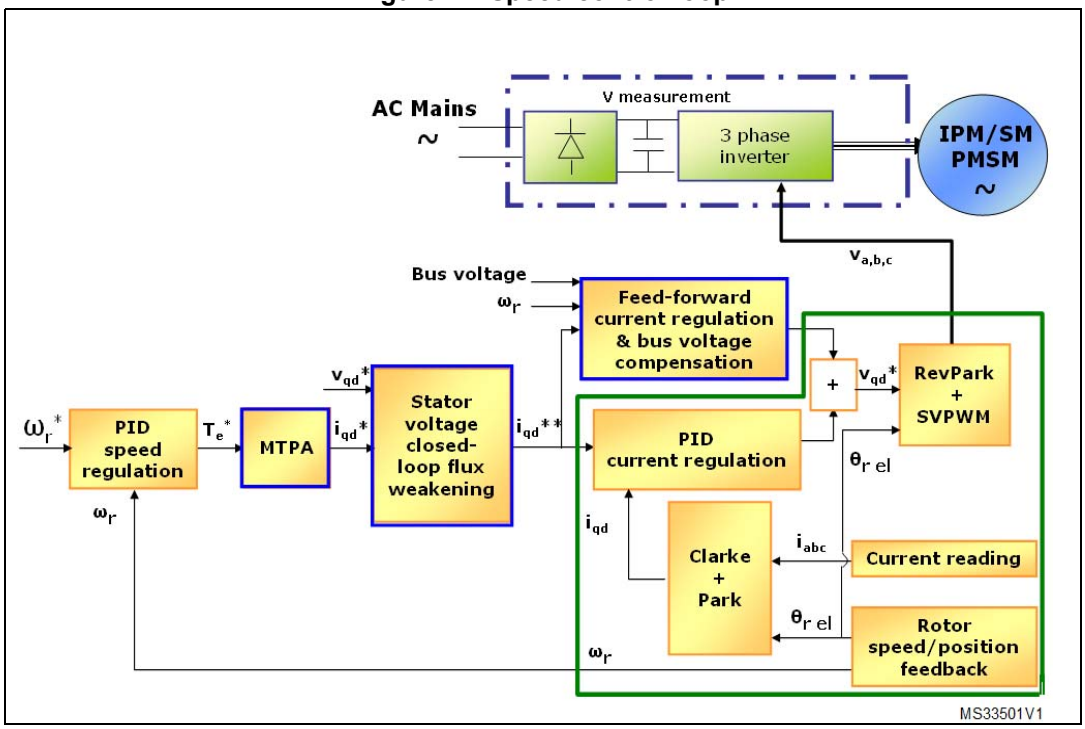


Table 1. References

Reference	Detail
Section 4.6: PMSM maximum torque per ampere (MTPA) control	Explains the MTPA (maximum-torque-per-ampere) strategy optimized for IPMSM.
Section 4.8: Flux-weakening control	Explains the flux-weakening control.
Section 4.7: Feed-forward current regulation	Shows how to take advantage of the feed-forward current regulation.

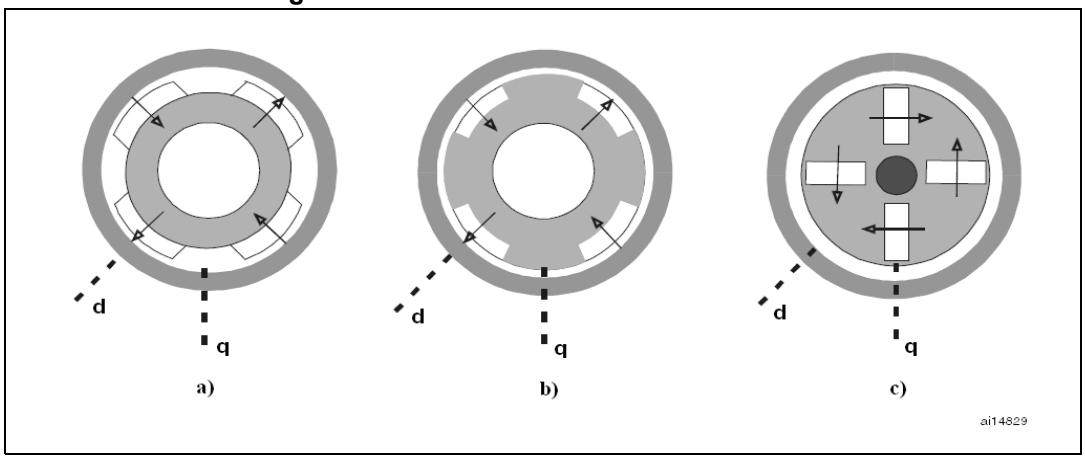
Figure 11: Speed control loop shows the speed control loop built around the 'core' torque control loop, plus additional specific features offered by this motor control library (see *Table 1: References*). Each of them can be set as an option, depending on the motor being used and user needs, via the ST MC Workbench GUI, which generates the .h file used to correctly initialize the MCA during its boot stage.

4.4 PM motor structures

Two different PM motor constructions are available:

- In drawing a) in *Figure 12*, the magnets are glued to the surface of the rotor, and this is the reason why it is referred to as SM-PMSM (surface mounted PMSM)
- In drawings b) and c) in *Figure 12*, the magnets are embedded in the rotor structure. This construction is known as IPMSM (interior PMSM)

Figure 12. Different PM motor constructions



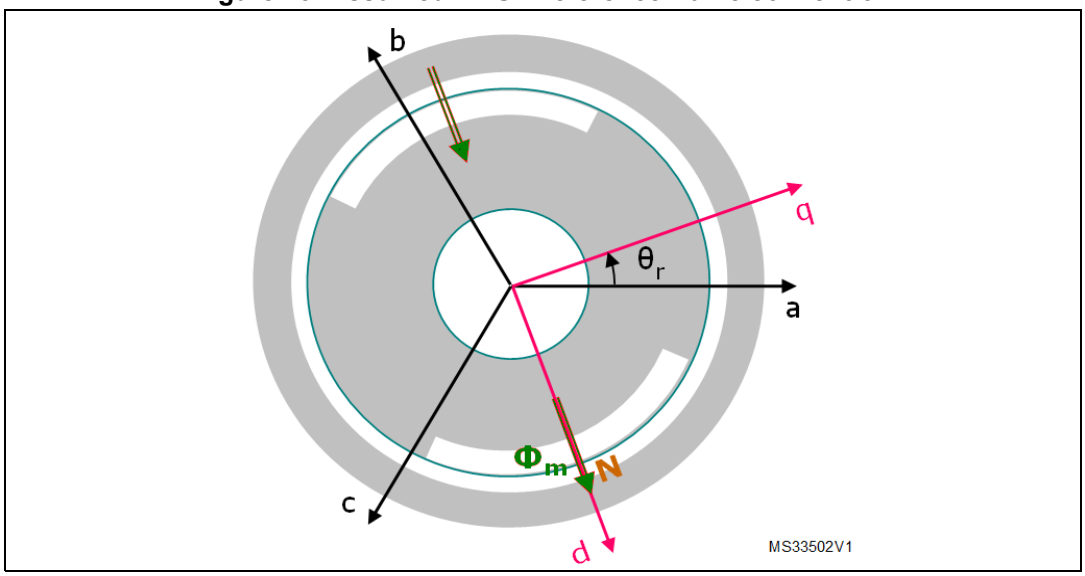
SM-PMSMs inherently have an isotropic structure, which means that the direct and quadrature inductances L_d and L_q are the same. Usually, their mechanical structure allows a wider airgap which, in turn, means lower flux weakening capability.

On the other hand, IPMSMs show an anisotropic structure (with $L_d < L_q$, typically), slight in the b) construction (called inset PM motor), strong in the c) configuration (called buried or radial PM motor). This peculiar magnetic structure can be exploited (as explained in *Section 4.6: PMSM maximum torque per ampere (MTPA) control*) to produce a greater amount of electromagnetic torque. their fine mechanical structure usually shows a narrow airgap, thus giving good flux weakening capability.

This firmware library is optimized for use in conjunction with SM-PMSMs and IPMSMs. machines.

4.5 PMSM fundamental equations

Figure 13. Assumed PMSM reference frame convention



With reference to *Figure 13*, the motor voltage and flux linkage equations of a PMSM (SM-PMSM or IPMSM) are generally expressed as:

$$v_{abc_s} = r_s i_{abc_s} + \frac{d\lambda_{abc_s}}{dt}$$

$$\lambda_{abc_s} = \begin{bmatrix} L_{ls}+L_{ms} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{ls}+L_{ms} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{ls}+L_{ms} \end{bmatrix} i_{abc_s} + \begin{bmatrix} \sin\theta_r \\ \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \Phi_m$$

where:

- r_s is the stator phase winding resistance
- L_{ls} is the stator phase winding leakage inductance
- L_{ms} is the stator phase winding magnetizing inductance; in case of an IPMSM, self and mutual inductances have a second harmonic component L_{2s} proportional to $\cos(2\theta_r + k \times 2\pi/3)$, with $k = 0 \pm 1$, in addition to the constant component L_{ms}(neglecting higher-order harmonics)
- θ_r is the rotor electrical angle
- Φ_m is the flux linkage due to permanent magnets

The complexity of these equations is apparent, as the three stator flux linkages are mutually coupled, and as they are dependent on the rotor position, which is time-varying and a function of the electromagnetic and load torques.

The reference frame theory simplifies the PM motor equations by changing a set of variables that refers the stator quantities abc (that can be visualized as directed along axes each 120° apart) to qd components, directed along a 90° apart axes, rotating synchronously with the rotor, and vice versa. The d “direct” axis is aligned with the rotor flux, while the q “quadrature” axis leads at 90 degrees in the positive rolling direction.

The motor voltage and flux equations are simplified to:

$$\begin{cases} v_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_r \lambda_{ds} \\ v_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_r \lambda_{qs} \end{cases}$$

$$\begin{cases} \lambda_{qs} = L_{qs} i_{qs} \\ \lambda_{ds} = L_{ds} i_{ds} + \Phi_m \end{cases}$$

For an SM-PMSM, the inductances of the d- and q- axis circuits are the same (refer to *Section 4.4: PM motor structures*), that is:

$$L_s = L_{qs} = L_{ds} = L_{ls} + \frac{3L_{ms}}{2}$$

On the other hand, IPMSMs show a salient magnetic structure; thus, their inductances can be written as:

$$L_{qs} = L_{ls} + \frac{3(L_{ms} + L_{2s})}{2}$$
$$L_{ds} = L_{ls} + \frac{3(L_{ms} - L_{2s})}{2}$$

4.5.1 SM-PMSM field-oriented control (FOC)

The equations below describe the electromagnetic torque of an SM-PMSM:

$$T_e = \frac{3}{2}\bar{p}(\lambda_{d_s} i_{q_s} - \lambda_{q_s} i_{d_s}) = \frac{3}{2}\bar{p}(L_s i_{d_s} i_{q_s} + \Phi_m i_{q_s} - L_s i_{q_s} i_{d_s})$$

$$T_e = \frac{3}{2}\bar{p}(\Phi_m i_{q_s})$$

The last equation makes it clear that the quadrature current component i_{qs} has linear control on the torque generation, whereas the current component i_{ds} has no effect on it (as mentioned above, these equations are valid for SM-PMSMs).

Therefore, if I_s is the motor rated current, then its maximum torque is produced for $i_{qs} = I_s$ and $i_{ds} = 0$ (in fact $I_s = \sqrt{i_{q_s}^2 + i_{d_s}^2}$). In any case, it is clear that, when using an SM-PMSM, the torque/current ratio is optimized by letting $i_{ds} = 0$. This choice corresponds to the MTPA (maximum-torque-per-ampere) control for isotropic motors.

On the other hand, the magnetic flux can be weakened by acting on the direct axis current i_{ds}; this extends the achievable speed range, but at the cost of a decrease in maximum quadrature current i_{qs}, and hence in the electromagnetic torque supplied to the load (see *Section 4.8: Flux-weakening control* for details about the Flux weakening strategy).

In conclusion, by regulating the motor currents through their components i_{qs} and i_{ds}, FOC manages to regulate the PMSM torque and flux. Current regulation is achieved by means of what is usually called a “synchronous frame CR-PWM”.

4.6 PMSM maximum torque per ampere (MTPA) control

The electromagnetic torque equation of an IPMSM is

$$T_e = \frac{3}{2}\bar{p}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) = \frac{3}{2}\bar{p}(L_{ds} i_{ds} i_{qs} + \Phi_m i_{qs} - L_{qs} i_{qs} i_{ds})$$

$$T_e = \frac{3}{2}\bar{p}\Phi_m i_{qs} + \frac{3}{2}\bar{p}(L_{ds} - L_{qs}) i_{qs} i_{ds}$$

The first term in this expression is the PM excitation torque. The second term is the so-called reluctance torque, which represents an additional component due to the intrinsic salient magnetic structure. Besides, since $L_d < L_q$ typically, reluctance and excitation torques have the same direction only if $i_{ds} < 0$.

Considering the torque equation, it can be pointed out that the current components i_{qs} and i_{ds} both have a direct influence on the torque generation.

The aim of the MTPA (maximum-torque-per-ampere) control is to calculate the reference currents (i_{qs}, i_{ds}) which maximize the ratio between produced electromagnetic torque and copper losses (under the following condition).

$$I_s = \sqrt{i_{qs}^2 + i_{ds}^2} \leq I_n$$

Therefore, given a set of motor parameters (pole pairs, direct and quadrature inductances L_d and L_q, magnets flux linkage, nominal current), the MTPA trajectory is identified as the locus of (i_{qs}, i_{ds}) pairs that minimizes the current consumption for each required torque (see *Figure 14*).

This feature can be activated through correct settings in .h parameter files (generated by the ST MC Workbench GUI) used to initialize the MC Application during its boot stage.

In confidential distribution, the classes that implement the MTPA algorithm are provided as compiled object files. The source code is available free of charge from ST on request. Please contact your nearest ST sales office.

Figure 14. MTPA trajectory

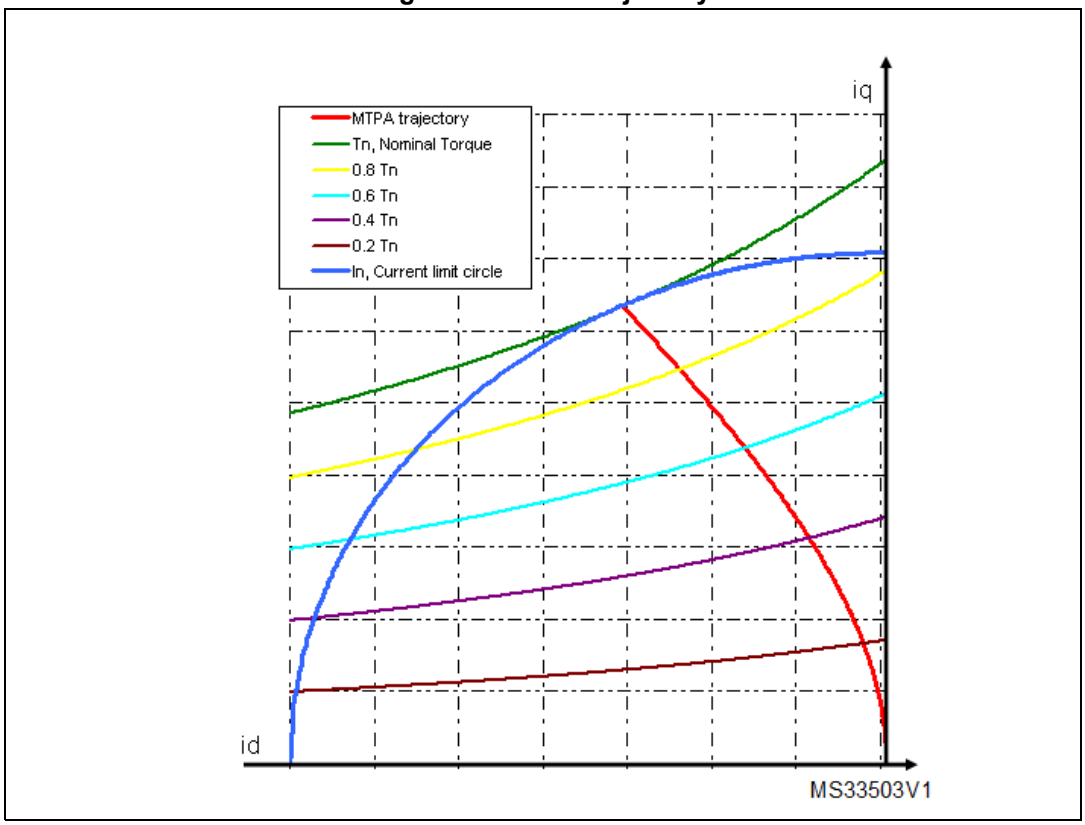
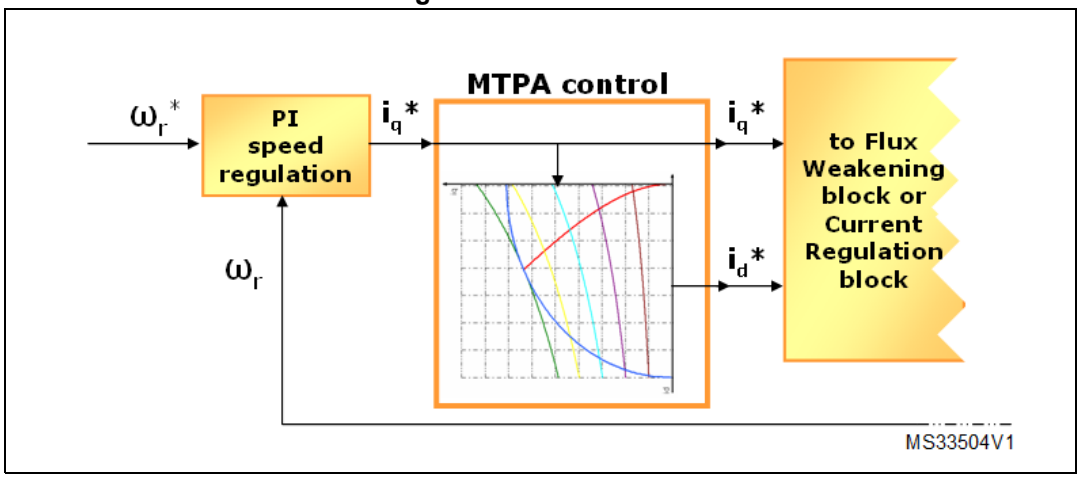


Figure 15 shows the MTPA strategy implemented inside a speed-control loop. In this case, i_{q*} (output of the PI regulator) is fed to the MTPA function, i_{d*} is chosen by entering the linear interpolated trajectory.

Figure 15. MTPA control



In all cases, by acting on the direct axis current i_{ds}, the magnetic flux can be weakened so as to extend the achievable speed range. As a consequence of entering this operating region, the MTPA path is left (see *Section 4.8: Flux-weakening control* for details about the flux-weakening strategy).

In conclusion, by regulating the motor currents through their i_{qs} and i_{ds} components, FOC manages to regulate the PMSM torque and flux. Current regulation is then achieved by means of what is usually called a “synchronous frame CR-PWM”.

4.7 Feed-forward current regulation

The feed-forward feature provided by this firmware library aims at improving the performance of the CR-PWM (current-regulated pulse width modulation) part of the motor drive.

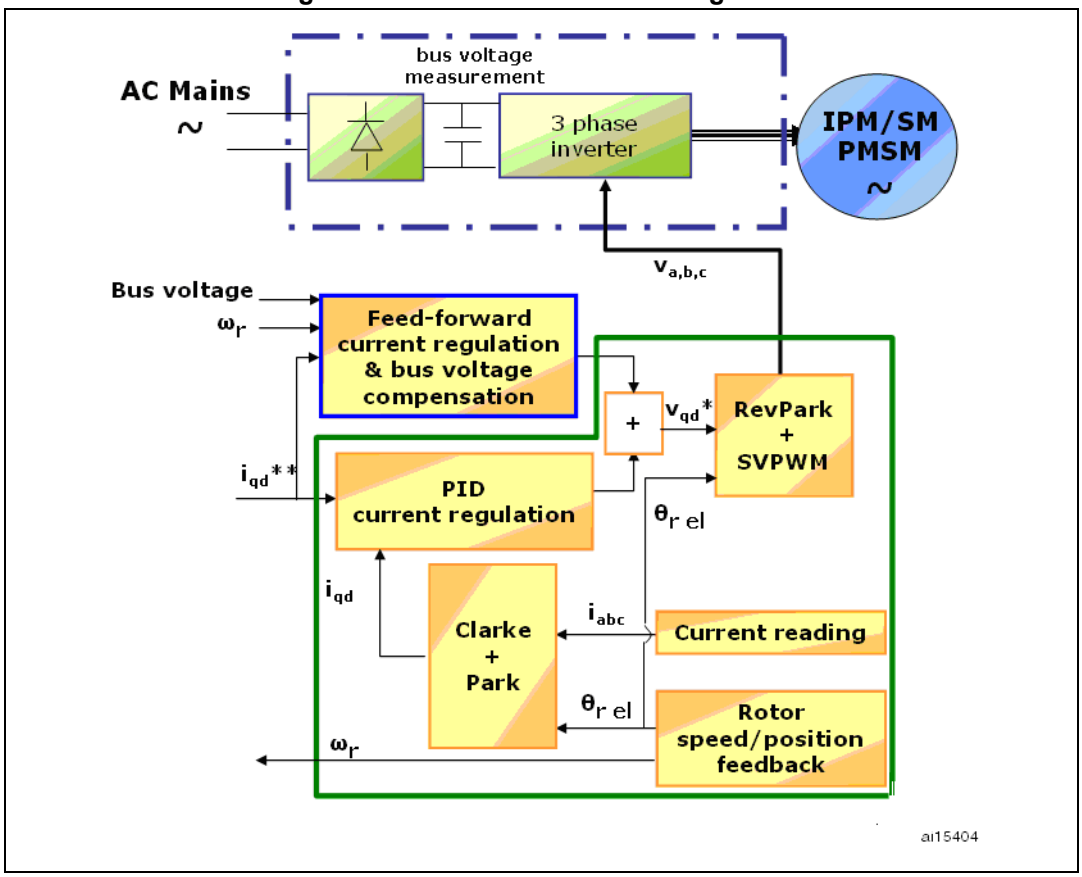
It calculates in advance the v_q* and v_d* stator voltage commands required to feed the motor with the i_q** and i_d** current references. By doing so, it backs up the standard PID current regulation (see *Figure 16*).

The feed-forward feature works in the synchronous reference frame and requires good knowledge of some machine parameters, such as the winding inductances L_d and L_q (or L_s if an SM-PMSM is used) and the motor voltage constant K_e.

The feed-forward algorithm has been designed to compensate for the frequency-dependent back emf’s and cross-coupled inductive voltage drops in permanent magnet motors. As a result, the q-axis and d-axis PID current control loops become linear, and a high performance current control is achieved.

As a further effect, since the calculated stator voltage commands v_q* and v_d* are compensated according to the present DC voltage measurement, a bus voltage ripple compensation is accomplished.

Figure 16. Feed-forward current regulation



Depending on certain overall system parameters, such as the DC bulk capacitor size, electrical frequency required by the application, and motor parameters, the feed-forward functionality can provide a major or a poor contribution to the motor drive. It is therefore recommended that you assess the resulting system performance and enable the functionality only if a valuable effect is measured.

This feature can be activated through proper settings in .h parameter files (generated by the ST MC Workbench GUI) used to initialize the MCA during its boot stage.

In confidential distribution, the classes that implement the feed-forward algorithm are provided as compiled object files. The source code is available free of charge from ST on request. Please contact your nearest ST sales office.

4.8 Flux-weakening control

The purpose of the flux-weakening functionality is to expand the operating limits of a permanent-magnet motor by reaching speeds higher than rated, as many applications require under operating conditions where the load is lower than rated. Here, the rated speed is considered to be the highest speed at which the motor can still deliver maximum torque.

The magnetic flux can be weakened by acting on direct axis current i_d; given a motor rated current I_n, such as $I_n = \sqrt{i_q^2 + i_d^2}$, if we choose to set id ≠ 0, then the maximum available quadrature current i_q is reduced. Consequently, in case of an SM-PMSM, as shown in *Section 4.5.1*, the maximum deliverable electromagnetic torque is also reduced. On the

other hand, for an IPM motor, acting separately on i_d causes a deviation from the MTPA path (as explained in *Section 4.6: PMSM maximum torque per ampere (MTPA) control*).

"Closed-loop" flux weakening has been implemented. Accurate knowledge of machine parameters is not required, which strongly reduces sensitivity to parameter deviation (see [3]-[4] in Appendix *Section A.1: References*). This scheme is suitable for both IPMSMs and SM-PMSMs.

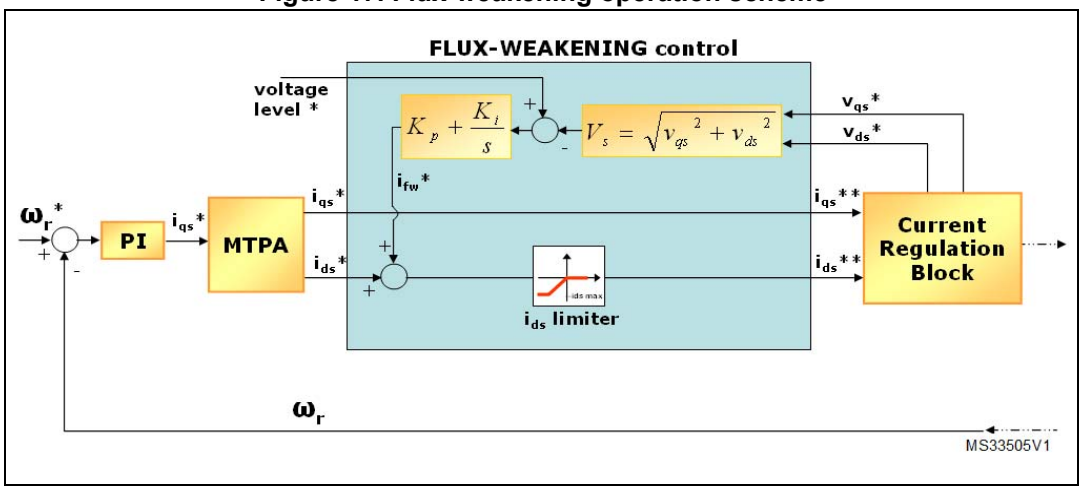
The control loop is based on stator voltage monitoring (*Figure 17* shows the diagram).

The current regulator output V_s is checked against a settled threshold ("voltage level*" parameter). If V_s is beyond that limit, the flux-weakening region is entered automatically by regulating a control signal, i_{fw}*, that is summed up to i_{ds}*, the output of the MTPA controller. This is done by means of a PI regulator (whose gain can be tuned in real-time) in order to prevent the saturation of the current regulators. It clearly appears, then, that the higher the voltage level* parameter is settled (by keeping up current regulation), the higher the achieved efficiency and maximum speed.

If V_s is smaller than the settled threshold, then i_{fw} decreases to zero and the MTPA block resumes control.

The current i_{ds}** output from the flux-weakening controller must be checked against i_{ds} max to avoid the demagnetization of the motor.

Figure 17. Flux-weakening operation scheme



This feature can be activated through correct settings in .h parameter files (generated by the ST MC Workbench GUI) used to initialize the MC Application during its 'boot' stage.

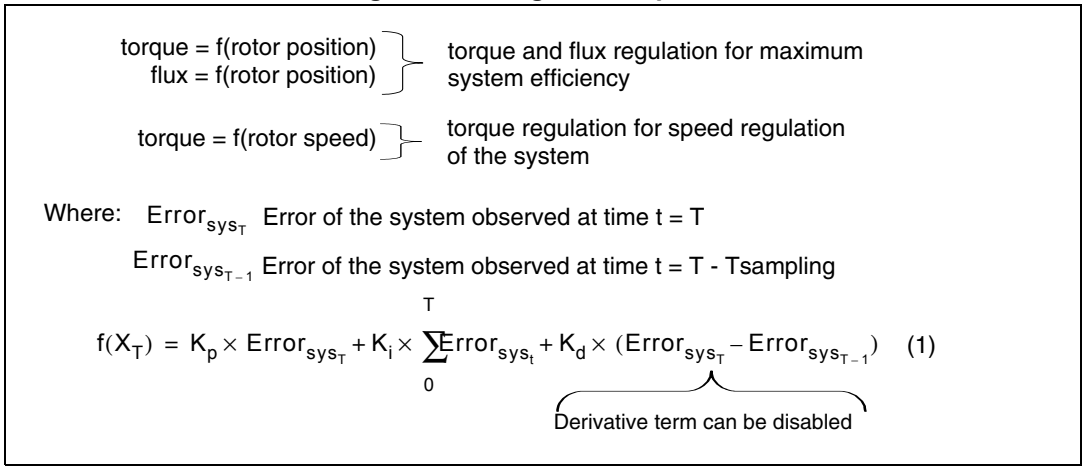
In confidential distribution, the classes that implement the flux weakening algorithm are provided as compiled object files. The source code is available free of charge from ST on request. Please contact your nearest ST sales office.

4.9 PID regulator theoretical background

The regulators implemented for Torque, Flux and Speed are actually Proportional Integral Derivative (PID) regulators. PID regulator theory and tuning methods are subjects which have been extensively discussed in technical literature. This section provides a basic reminder of the theory.

PID regulators are useful to maintain a level of torque, flux or speed according to a desired target.

Figure 18. PID general equation


torque = f(rotor position)
flux = f(rotor position)
torque and flux regulation for maximum system efficiency
torque = f(rotor speed)
torque regulation for speed regulation of the system
Where: $Error_{sys_T}$ Error of the system observed at time t = T
$Error_{sys_{T-1}}$ Error of the system observed at time t = T - Tsampling
$f(X_T) = K_p \times Error_{sys_T} + K_i \times \sum_0^T Error_{sys_t} + K_d \times (Error_{sys_T} - Error_{sys_{T-1}})$ (1)
Derivative term can be disabled

Equation 1 corresponds to a classical PID implementation, where:

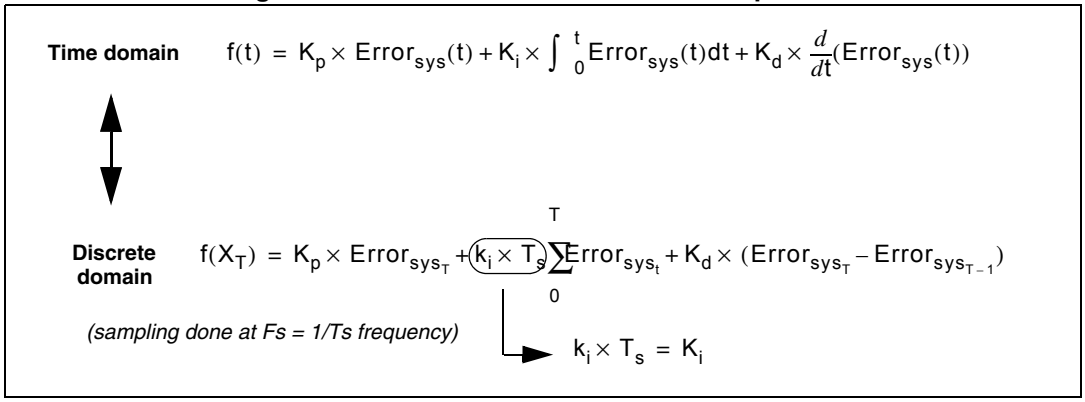
- K_p is the proportional coefficient.
- K_i is the integral coefficient.
- K_d is the differential coefficient.

4.9.1 Regulator sampling time setting

The sampling time needs to be modified to adjust the regulation bandwidth. As an accumulative term (the integral term) is used in the algorithm, increasing the loop time decreases its effects (accumulation is slower and the integral action on the output is delayed). Inversely, decreasing the loop time increases its effects (accumulation is faster and the integral action on the output is increased). This is why this parameter has to be adjusted prior to setting up any coefficient of the PID regulator.

In order to keep the CPU load as low as possible and as shown in equation (1) in *Figure 18*, the sampling time is directly part of the integral coefficient, thus avoiding an extra multiplication. *Figure 19* describes the link between the time domain and the discrete system.

Figure 19. Time domain to discrete PID equations


Time domain
$f(t) = K_p \times Error_{sys}(t) + K_i \times \int_0^t Error_{sys}(t)dt + K_d \times \frac{d}{dt}(Error_{sys}(t))$
Discrete domain
$f(X_T) = K_p \times Error_{sys_T} + (k_i \times T_s) \sum_0^T Error_{sys_t} + K_d \times (Error_{sys_T} - Error_{sys_{T-1}})$
(sampling done at Fs = 1/Ts frequency)
$k_i \times T_s = K_i$

In theory, the higher the sampling rate, the better the regulation. In practice, you must keep in mind that:

- The related CPU load will grow accordingly.
- For speed regulation, there is absolutely no need to have a sampling time lower than the refresh rate of the speed information fed back by the external sensors; this becomes especially true when Hall sensors are used while driving the motor at low speed.

4.10 A priori determination of flux and torque current PI gains

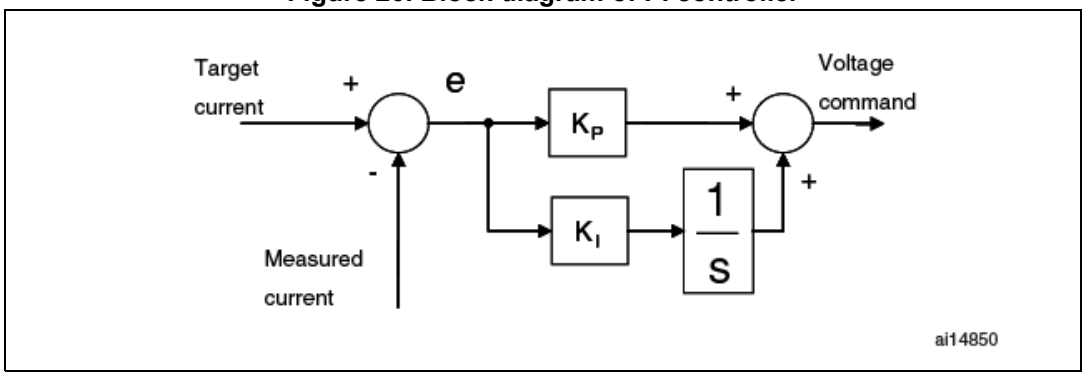
This section provides a criterion for the computation of the initial values of the torque/flux PI parameters (K_I and K_P). This criterion is also used by the ST MC Workbench in its computation.

To calculate these starting values, it is required to know the electrical characteristics of the motor (stator resistance R_s and inductance L_s) and the electrical characteristics of the hardware (shunt resistor R_{Shunt}, current sense amplification network A_{Op} and the direct current bus voltage $V_{Bus}DC$).

The derivative action of the controller is not considered using this method.

Figure 20 shows the PI controller block diagram used for torque or flux regulation.

Figure 20. Block diagram of PI controller

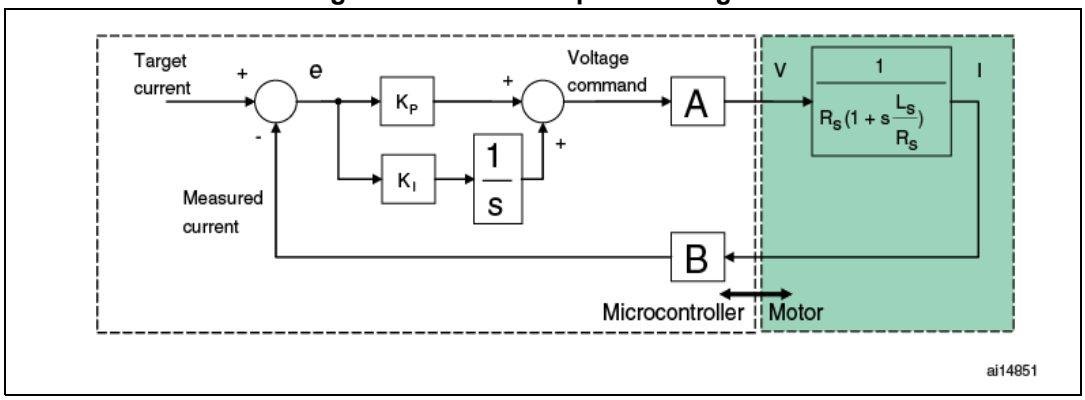


For this analysis, the motor electrical characteristics are assumed to be isotropic with respect to the q and d axes. It is assumed that the torque and flux regulators have the same starting value of K_P and the same K_I value.

Figure 21 shows the closed loop system in which the motor phase is modelled using the resistor-inductance equivalent circuit in the “locked-rotor” condition.

Block “A” is the proportionality constant between the software variable storing the voltage command (expressed in digit) and the real voltage applied to the motor phase (expressed in Volt). Likewise, block “B” is the is the proportionality constant between the real current (expressed in Ampere) and the software variable storing the phase current (expressed in digit).

Figure 21. Closed loop block diagram

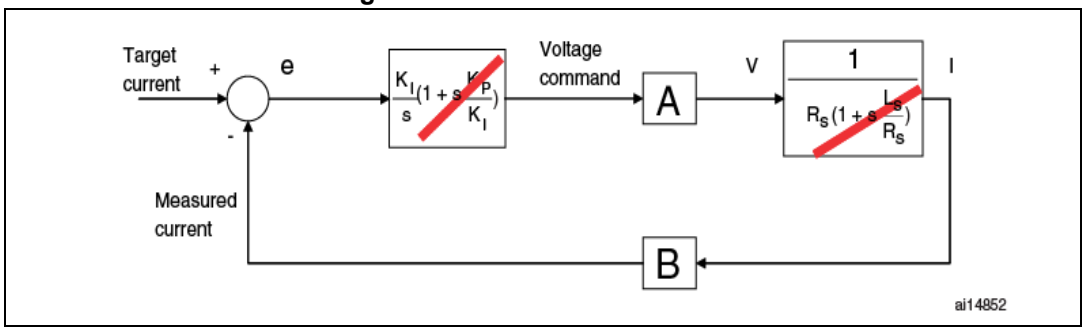


The transfer functions of the two blocks “A” and “B” are expressed by the following formulas:

$A = \frac{V_{Bus}DC}{2^{16}}$ and $B = \frac{R_{shunt}A_{op}2^{16}}{3.3}$, respectively.

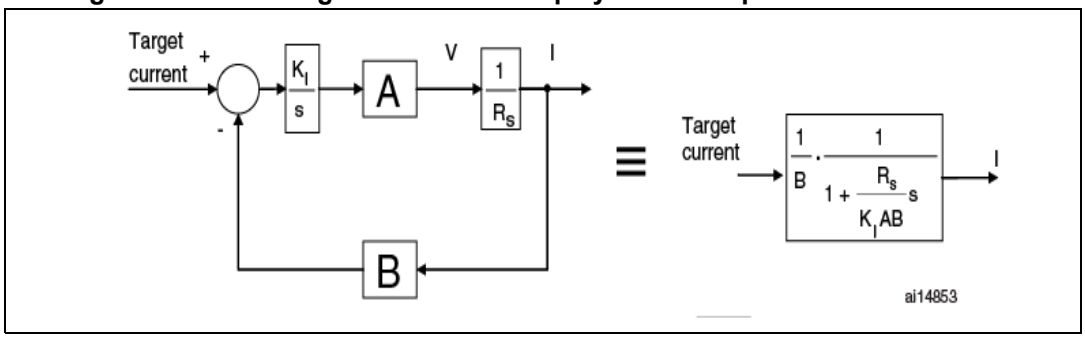
By putting $K_P/K_I = L_S/R_S$, it is possible to perform pole-zero cancellation as described in *Figure 22*.

Figure 22. Pole-zero cancellation



In this condition, the closed loop system is brought back to a first-order system and the dynamics of the system can be assigned using a proper value of K_I. See *Figure 23*.

Figure 23. Block diagram of closed loop system after pole-zero cancellation



Note: The parameters used inside the PI algorithms must be integer numbers; thus, calculated KI and KP values have to be expressed as fractions (dividend/divisor).

Moreover, the PI algorithm does not include the PI sampling time (T) in the computation of the integral part. See the following formula:

$$k_i \int_0^t e(\tau)d\tau = k_i T \sum_{k=1}^{n} e(kT) = K_i \sum_{k=1}^{n} e(kT)$$

Since the integral part of the controller is computed as a sum of successive errors, it is required to include T in the K_I computation.

The final formula can be expressed as:

$$K_P = L_S \frac{\omega_C}{AB} K_P DIV$$

$$K_i = \frac{R_S \cdot \omega_C \cdot K_i DIV}{AB} \cdot T$$

$$AB = \frac{V_{Bus}DC \cdot R_{shunt} \cdot A_{op}}{3.3}$$

Usually, it is possible to set ω_C (the bandwidth of the closed loop system) to 1500 rad/s, to obtain a good trade-off between dynamic response and sensitivity to the measurement noise.

4.11 Space vector PWM implementation

Figure 24 shows the stator voltage components V_α and V_β while *Figure 25* illustrates the corresponding PWM for each of the six space vector sectors.

Figure 24. V_α and V_β stator voltage components

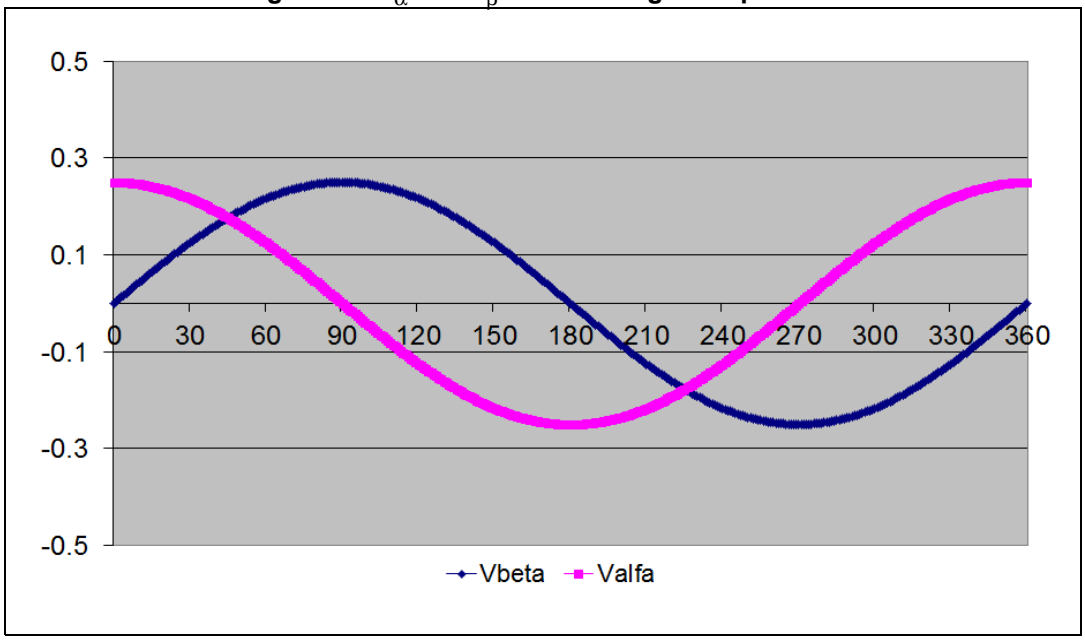
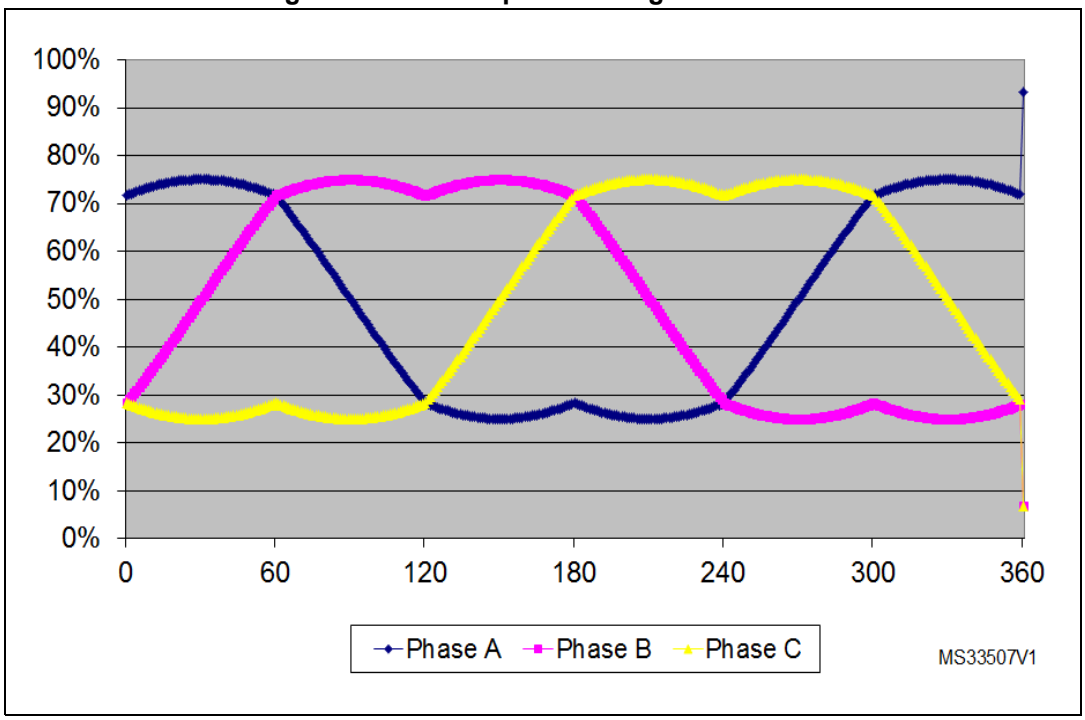


Figure 25. SVPWM phase voltage waveforms



With the following definitions for: $U_\alpha = \sqrt{3} \times T \times V_\alpha$, $U_\beta = -T \times V_\beta$ and $X = U_\beta$, $Y = \frac{U_\alpha + U_\beta}{2}$ and $Z = \frac{U_\beta - U_\alpha}{2}$.

The literature demonstrates that the space vector sector is identified by the conditions shown in *Table 2*.

Table 2. Sector identification

	Y < 0			**Y ≥ 0**		
	Z < 0	**Z ≥ 0**		**Z < 0**		**Z ≥ 0**
		X ≤ 0	**X > 0**	**X ≤ 0**	**X > 0**	
Sector	V	IV	III	VI	I	II

The duration of the positive pulse widths for the PWM applied on Phase A, B and C are respectively computed by the following relationships:

Sector I, IV: $t_A = \frac{T + X - Z}{2}$, $t_B = t_A + Z$, $t_C = t_B - X$

Sector II, V: $t_A = \frac{T + Y - Z}{2}$, $t_B = t_A + Z$, $t_C = t_A - Y$

Sector III, VI: $t_A = \frac{T - X + Y}{2}$, $t_B = t_C + X$, $t_C = t_A - Y$, where T is the PWM period.

Considering that the PWM pattern is center-aligned and that the phase voltages must be centered at 50% of duty cycle, it follows that the values to be loaded into the PWM output compare registers are given respectively by:

Sector I, IV: $\text{TimePhA} = \frac{T}{4} + \frac{T/2 + X - Z}{2}$, $\text{TimePhB} = \text{TimePhA} + Z$, $\text{TimePhC} = \text{TimePhB} - X$

Sector II, V: $\text{TimePhA} = \frac{T}{4} + \frac{T/2 + Y - Z}{2}$, $\text{TimePhB} = \text{TimePhA} + Z$, $\text{TimePhC} = \text{TimePhA} - Y$

Sector III,VI: $\text{TimePhA} = \frac{T}{4} + \frac{T/2 + Y - X}{2}$, $\text{TimePhB} = \text{TimePhC} + X$, $\text{TimePhC} = \text{TimePhA} - Y$

4.12 Detailed explanation about reference frame transformations

PM synchronous motors show very complex and time-varying voltage equations.

By changing a set of variables that refers stator quantities to a frame of reference synchronous with the rotor, it is possible to reduce the complexity of these equations.

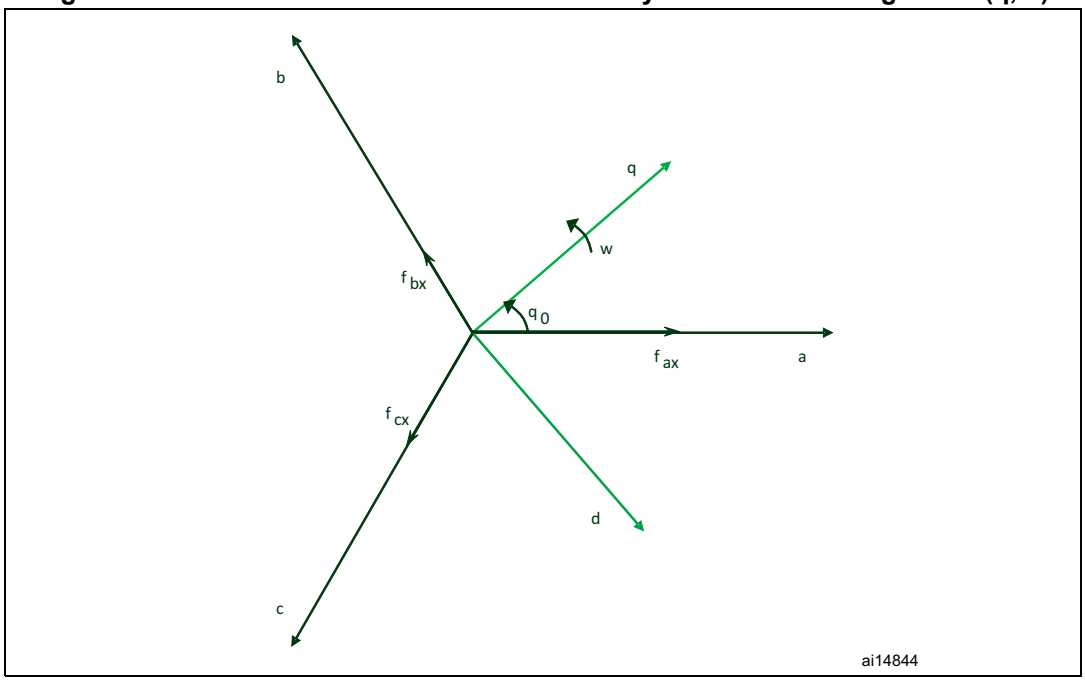
This strategy is often referred to as the Reference-Frame theory [1].

Supposing f_{ax}, f_{bx}, f_{cx} are three-phase instantaneous quantities directed along axis, each displaced by 120 degrees, where x can be replaced with s or r to treat stator or rotor quantities (see *Figure 26*); supposing f_{qx}, f_{dx}, f_{0x} are their transformations, directed along paths orthogonal to each other; the equations of transformation to a reference frame (rotating at an arbitrary angular velocity ω) can be expressed as:

$$f_{qdox} = \begin{bmatrix} f_{qx} \\ f_{dx} \\ f_{0x} \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_{ax} \\ f_{bx} \\ f_{cx} \end{bmatrix}$$

where θ is the angular displacement of the (q, d) reference frame at the time of observation, and θ_0 that displacement at t=0 (see *Figure 26*).

Figure 26. Transformation from an *abc* stationary frame to a rotating frame (q, d)



With Clark's transformation, stator currents i_{as} and i_{bs} (which are directed along axes each displaced by 120 degrees) are resolved into currents $i\alpha$ and $i\beta$ on a stationary reference frame (α β).

An appropriate substitution into the general equations (given above) yields to:

$$i_\alpha = i_{as}$$

$$i_\beta = -\frac{i_{as} + 2i_{bs}}{\sqrt{3}}$$

In Park's change of variables, stator currents i_α and i_β, which belong to a stationary reference frame (α β), are resolved to a reference frame synchronous with the rotor and oriented so that the d-axis is aligned with the permanent magnets flux, so as to obtain i_{qs} and i_{ds}.

Consequently, with this choice of reference, we have:

$$i_{qs} = i_\alpha \cos\theta_r - i_\beta \sin\theta_r$$
$$i_{ds} = i_\alpha \sin\theta_r + i_\beta \cos\theta_r$$

On the other hand, reverse Park transformation takes back stator voltage v_q and v_d, belonging to a rotating frame synchronous and properly oriented with the rotor, to a stationary reference frame, so as to obtain v_α and v_β:

$$v_\alpha = v_{qs} \cos\theta_r + v_{ds} \sin\theta_r$$
$$v_\beta = -v_{qs} \sin\theta_r + v_{ds} \cos\theta_r$$

4.12.1 Circle limitation

As discussed above, FOC allows to separately control the torque and the flux of a 3-phase permanent magnet motor. After the two new values(v_d^* and v_q^*) of the stator voltage producing flux and torque components of the stator current have been independently computed by flux and torque PIDs, it is necessary to saturate the magnitude of the resulting

vector ($|\vec{V}^*|$) before passing them to the Reverse Park transformation and, finally, to the SVPWM block.

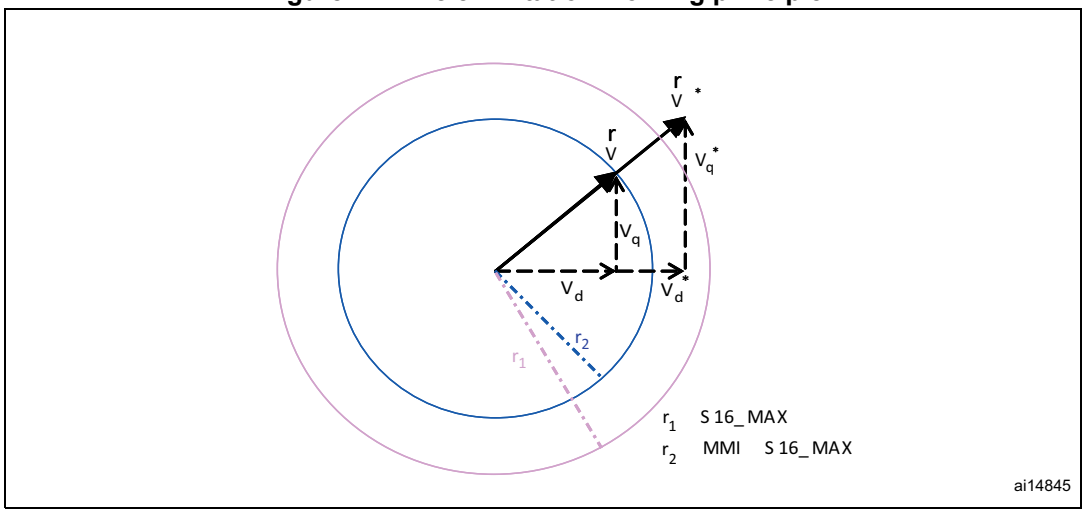
The saturation boundary is normally given by the value (S16_MAX=32767) which produces the maximum output voltage magnitude (corresponding to a duty cycle going from 0% to 100%).

Nevertheless, when using a single-shunt or three-shunt resistor configuration and depending on PWM frequency, it might be necessary to limit the maximum PWM duty cycle to guarantee the proper functioning of the stator currents reading block.

For this reason, the saturation boundary could be a value slightly lower than S16_MAX depending on PWM switching frequency when using a single-shunt or three-shunt resistor configuration.

The circle limitation function performs the discussed stator voltage components saturation, as illustrated in *Figure 27*.

Figure 27. Circle limitation working principle



V_d and V_q represent the saturated stator voltage components to be passed to the Reverse Park transformation function, while V_d^* and V_q^* are the outputs of the PID current controllers. From geometrical considerations, it is possible to draw the following relationship:

$$v_d = \frac{v_d^* \cdot MMI \cdot S16\_MAX}{|\vec{V}^*|}$$

$$v_q = \frac{v_q^* \cdot MMI \cdot S16\_MAX}{|\vec{V}^*|}$$

In order to speed up the computation of the above equations while keeping an adequate resolution, the value

$$\frac{MMI \cdot S16\_MAX^2}{|\vec{V}^*|}$$

is computed and stored in a look-up table for different values of $|\vec{V}^*|$ and MMI (Maximum Modulation Index).

5 Current sampling

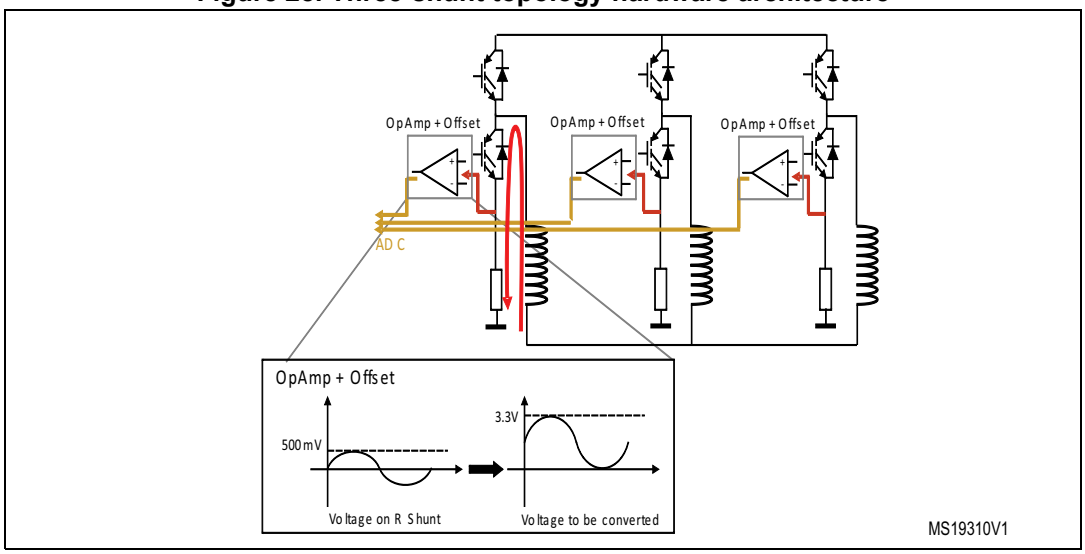
Section 4.3: Introduction to the PMSM FOC drive shows that current sampling plays a crucial role in PMSM field-oriented control. This motor control library provides complete modules for supporting three-shunt, single-shunt, and ICS topologies. Refer to sections *Section 5.1*, *Section 5.4*, *Section 5.5* respectively for further details.

The selection of decoding algorithm—to match the topology actually in use—can be performed through correct settings in the .h parameter files (generated by the ST MC Workbench GUI) used to initialize the MC Application during its boot stage.

5.1 Current sampling in three-shunt topology

Figure 28 shows the three-shunt topology hardware architecture.

Figure 28. Three-shunt topology hardware architecture



The three currents I_1, I_2, and I_3 flowing through a three-phase system follow the mathematical relation:

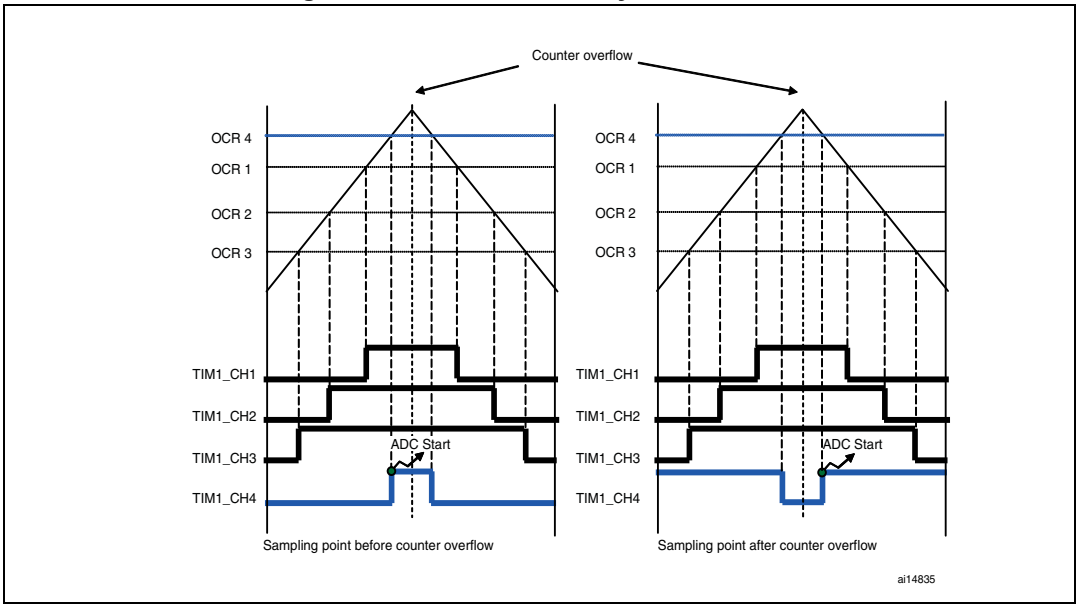
$$I_1 + I_2 + I_3 = 0$$

For this reason, to reconstruct the currents flowing through a generic three-phase load, it is sufficient to sample only two out of the three currents while the third one can be computed by using the above relation.

The flexibility of the STM32 A/D converter makes it possible to synchronously sample the two A/D conversions needed for reconstructing the current flowing through the motor. The ADC can also be used to synchronize the current sampling point with the PWM output using the external triggering capability of the peripheral. Owing to this, current conversions can be performed at any given time during the PWM period. To do this, the control algorithm uses the fourth PWM channel of TIM1 to synchronize the start of the conversions.

Figure 29 shows the synchronization strategy between the TIM1 PWM output and the ADC. The A/D converter peripheral is configured so that it is triggered by the rising edge of TIM1_CH4.

Figure 29. PWM and ADC synchronization



In this way, supposing that the sampling point must be set before the counter overflow, that is, when the TIM1 counter value matches the OCR4 register value during the upcounting, the A/D conversions for current sampling are started. If the sampling point must be set after the counter overflow, the PWM 4 output has to be inverted by modifying the CC4P bit in the TIM1_CCER register. Thus, when the TIM1 counter matches the OCR4 register value during the downcounting, the A/D samplings are started.

After execution of the FOC algorithm, the value to be loaded into the OCR4 register is calculated to set the sampling point for the next PWM period, and the A/D converter is configured to sample the correct channels.

Table 3. Three-shunt current reading, used resources (single drive, F103 LD/MD)

Adv. timer	DMA	ISR	ADC master	ADC slave	Note
TIM1	DMA1_CH1 DMA1_CH5	None	ADC1	ADC2	DMA is used to enable ADC injected conversion external trigger. Disabling is performed by software.

Table 4. Three-shunt current reading, used resources (Dual drive,F103 HD, F2x, F4x)

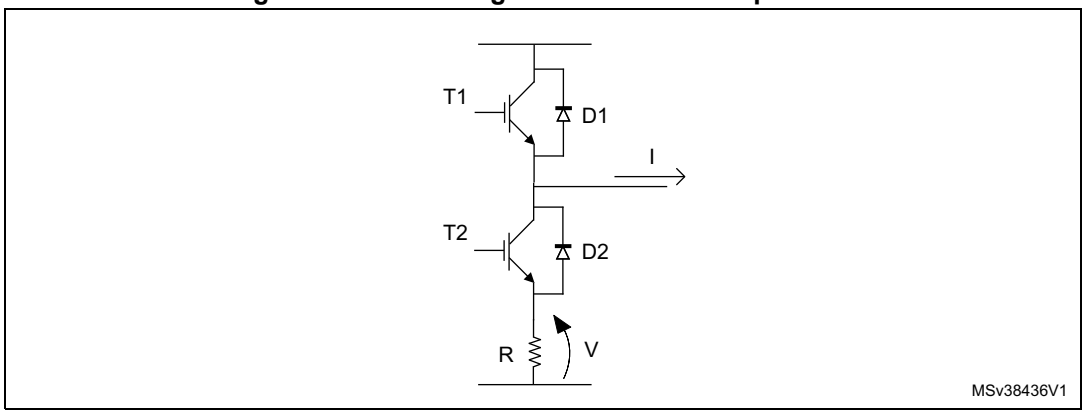
Adv. timer	DMA	ISR	ADC	Note
TIM1	DMA1_CH1	TIM1_UP	ADC1 ADC2	Used by first or second motor configured in three-shunt, according to user selection. ADC is used in time sharing. Trigger selection is performed in the TIM_UP ISR.
TIM8	None	TIM8_UP	ADC1 ADC2	Used by first or second motor configured in three-shunt, according to user selection. ADC is used in time sharing. Trigger selection is performed in the TIM_UP ISR.

Please refer to *Section 6: Current sensing and protection on embedded PGA* for STM32F30x microcontroller configuration

5.1.1 Tuning delay parameters and sampling stator currents in shunt resistor

Figure 30 shows one of the three inverter legs with the related shunt resistor:

Figure 30. Inverter leg and shunt resistor position



To indirectly measure the phase current I, it is possible to read the voltage V provided that the current flows through the shunt resistor R.

It is possible to demonstrate that, whatever the direction of current I, it always flows through the resistor R if transistor T2 is switched on and T1 is switched off. This implies that, in order to properly reconstruct the current flowing through one of the inverter legs, it is necessary to properly synchronize the conversion start with the generated PWM signals. This also means that current reading cannot be performed on a phase where the duty cycle applied to the low side transistor is either null or very short.

As discussed in *Section 5.1*, to reconstruct the currents flowing through a generic three-phase load, it is sufficient to simultaneously sample only two out of three currents, the third one being computed from the relation given in *Section 5.1*. Thus, depending on the space vector sector, the A/D conversion of voltage V will be performed only on the two phases where the duty cycles applied to the low side switches are the highest. Looking at *Figure 25*, you can deduct that, in sectors 1 and 6, the voltage on phase A shunt resistor can be discarded; likewise in sectors 2 and 3 for phase B, and in sectors 4 and 5 for phase C.

Moreover, in order to properly synchronize the two stator current reading A/D conversions, it is necessary to distinguish between the different situations that can occur depending on PWM frequency and applied duty cycles.

Note: The explanations below refer to space vector Section 1. They can be applied in the same manner to the other sectors.

Case 1: Duty cycle applied to Phase A low side switch is larger than DT+T_N

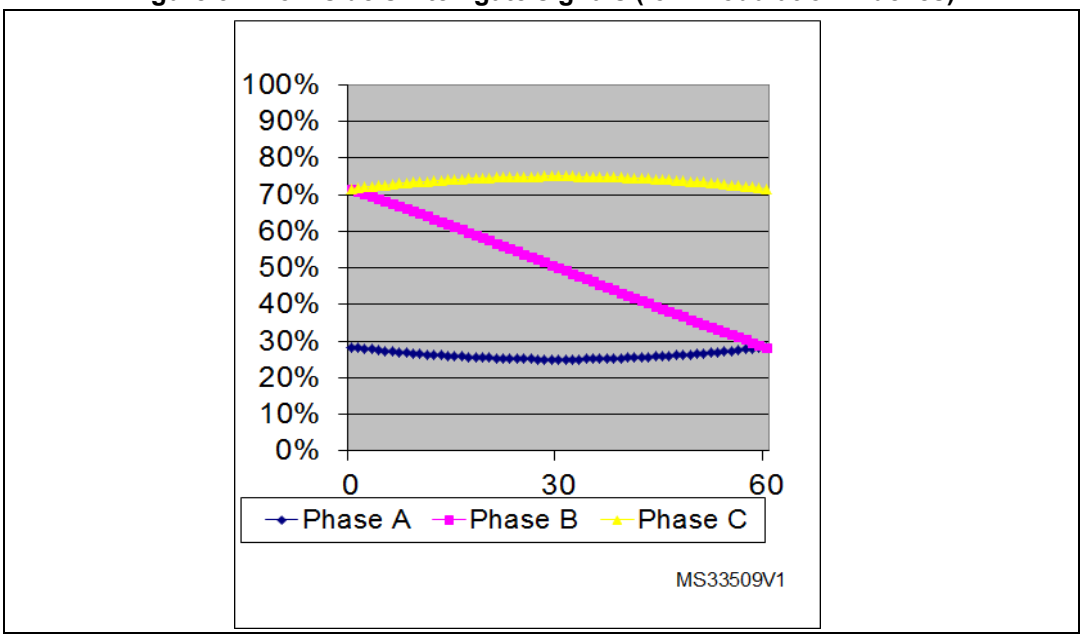
Where:

- DT is dead time.
- T_N is the duration of the noise induced on the shunt resistor voltage of a phase by the commutation of a switch belonging to another phase.
- T_S is the sampling time of the Root part number 1 A/D converter (the following consideration is made under the hypothesis that T_S < DT + T_N). Refer to the Root part number 1 reference manual for more detailed information.

This case typically occurs when SVPWM with low (<60%) modulation index is generated (see *Figure 31*). The modulation index is the applied phase voltage magnitude expressed as a percentage of the maximum applicable phase voltage (the duty cycle ranges from 0% to 100%).

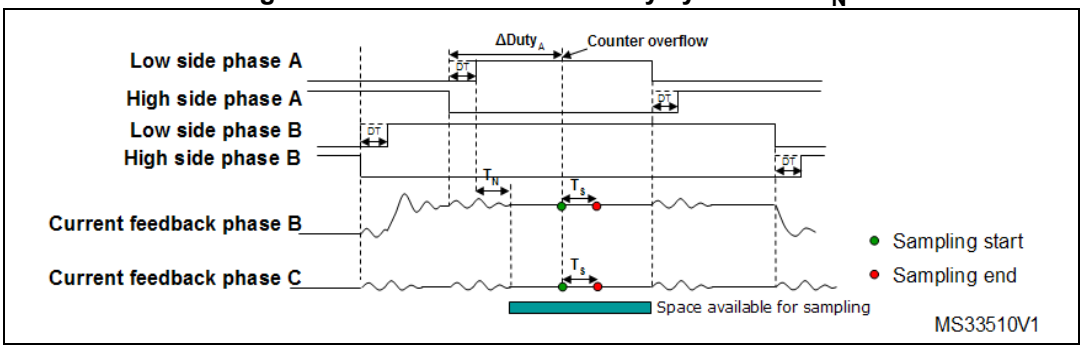
Figure 32 offers a reconstruction of the PWM signals applied to low side switches of phase A and B in these conditions, plus a view of the analog voltages measured on the Root part number 1 A/D converter pins for both phase B and C (the time base is lower than the PWM period).

Figure 31. Low-side switch gate signals (low modulation indexes)



Note: These current feedbacks are constant in Figure 32 because it is assumed that commutations on phase B and C have occurred out of the visualized time window. In this case, the two stator current sampling conversions can be performed synchronized with the counter overflow, as shown in Figure 32.

Figure 32. Low side Phase A duty cycle > DT+T_N



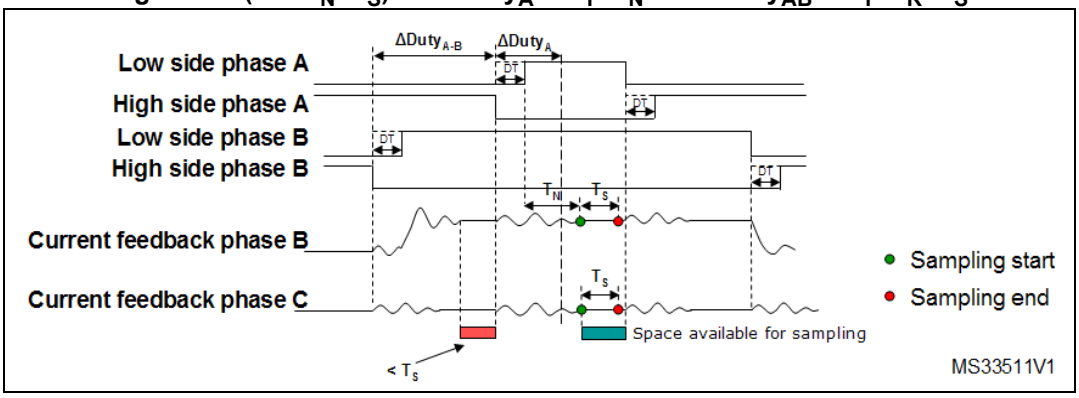
Case 2: (DT+T_N+T_S)/2 < $\Delta Duty_A$ < D_T+T_N and $\Delta Duty_{AB}$ < D_T+T_R+T_S

With the increase in modulation index, $\Delta Duty_A$ can have values smaller than D_T+T_N. Sampling synchronized with the counter overflow could be impossible.

In this case, the two currents can still be sampled between the two phase A low side commutations, but only after the counter overflow.

To avoid the acquisition of the noise induced on the phase B current feedback by phase A switch commutations, it is required to wait for the noise to be over (T_N). See *Figure 33*.

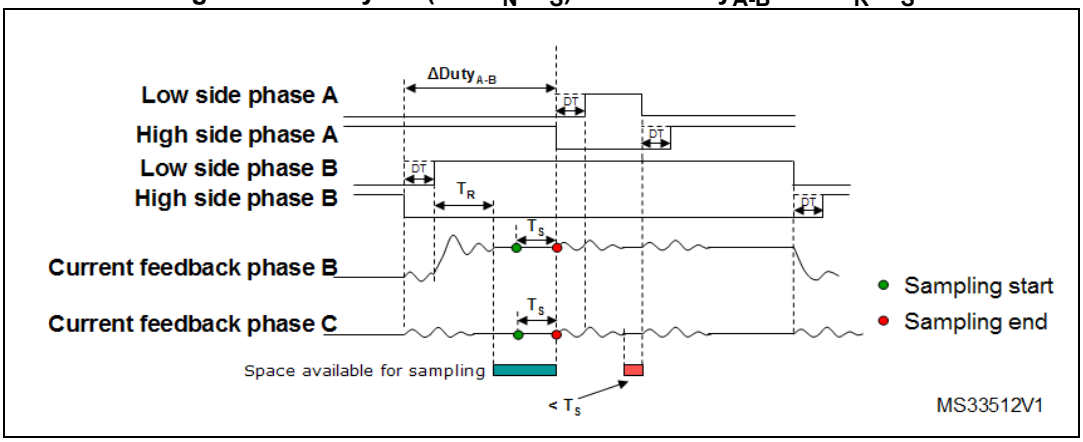
Figure 33. (DT+T_N+T_S)/2 < $\Delta Duty_A$ < D_T+T_N and $\Delta Duty_{AB}$ < D_T+T_R+T_S



Case 3: ΔDutyA < (DT+T_N+T_S)/2 and $\Delta Duty_{A-B}$>DT+T_R+T_S

In this case, it is no longer possible to sample the currents during phase A low-side switch-on. Anyway, the two currents can be sampled between phase B low-side switch-on and phase A high-side switch-off. The choice was made to sample the currents T_S µs before of phase A high-side switch-off (see *Figure 34*).

Figure 34. ΔDutyA < (DT+T_N+T_S)/2 and $\Delta Duty_{A-B}$>DT+T_R+T_S



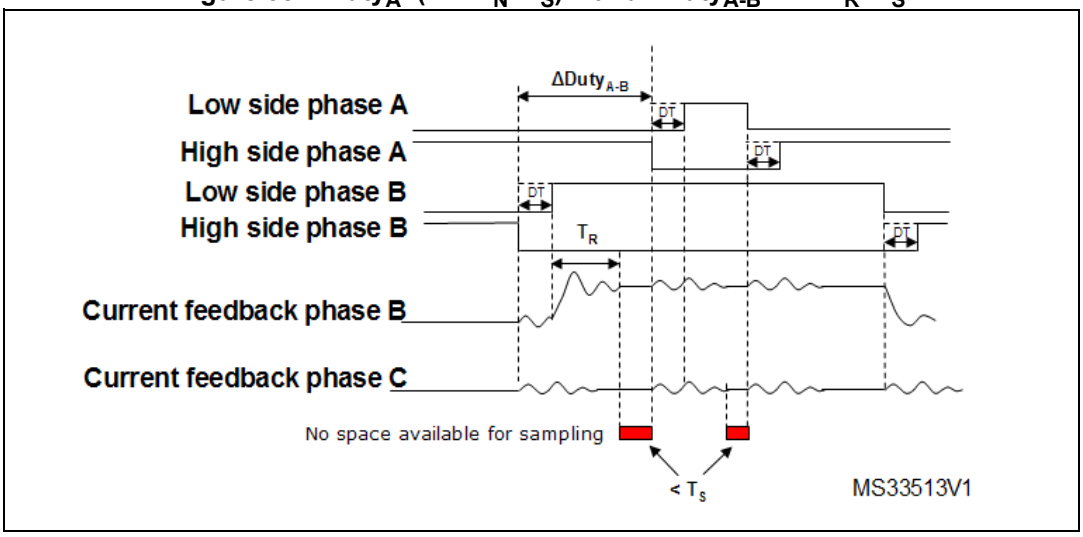
Case 4: $\Delta Duty_A$<(DT+T_N+T_S)/2 and $\Delta Duty_{A-B}$<DT+T_R+T_S

In this case, the duty cycle applied to phase A is so short that no current sampling can be performed between the two low-side commutations.

If the difference in duty cycles between phase B and A is not long enough to allow the A/D conversions to be performed between phase B low-side switch-on and phase A high-side switch-off, it is impossible to sample the currents (See *Figure 35*).

To avoid this condition, it is necessary to reduce the maximum modulation index or to decrease the PWM frequency.

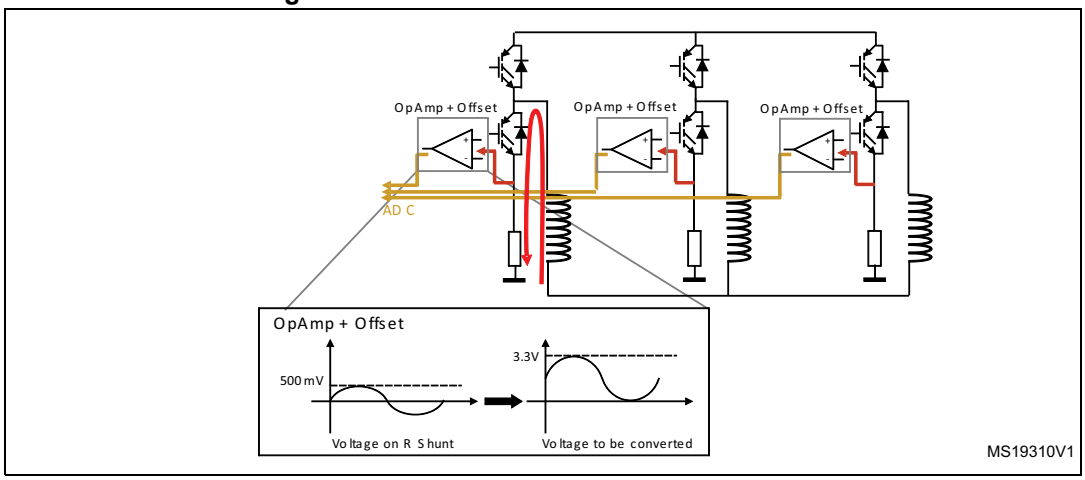
Figure 35. $\Delta Duty_A$<(DT+T_N+T_S)/2 and $\Delta Duty_{A-B}$<DT+T_R+T_S



5.2 Current sampling in three-shunt topology using one A/D converter

Figure 36 shows the three-shunt topology hardware architecture.

Figure 36. three-shunt hardware architecture



The three currents I1, I2 and I3 flowing through a three-phase system follow the mathematical relation:

$$I_1 + I_2 + I_3 = 0$$

For this reason, in order to rebuild the currents flowing through a generic three-phase load, it is sufficient to sample only two out of the three currents while the third one can be computed by using the above relation.

Unlike the case of current sapling with two ADCs, in the case of single ADC it is not possible to synchronously sample the two phase current A/D conversions, needed for reconstructing the current flowing through the motor, but they can be performed only in sequence mode.

The ADC can be used to synchronize the current sampling point with the PWM output using the external triggering capability of the peripheral. Owing to this, current conversion sequence can be performed at any given time during the PWM period.

To do this, the control algorithm uses the fourth PWM channel of TIM1 to synchronize the start of the conversion sequence.

Figure 37 and *Figure 38* show the synchronization strategy between the TIM1 PWM output and the ADC.

Figure 37. PWM and ADC synchronization ADC rising edge external trigger

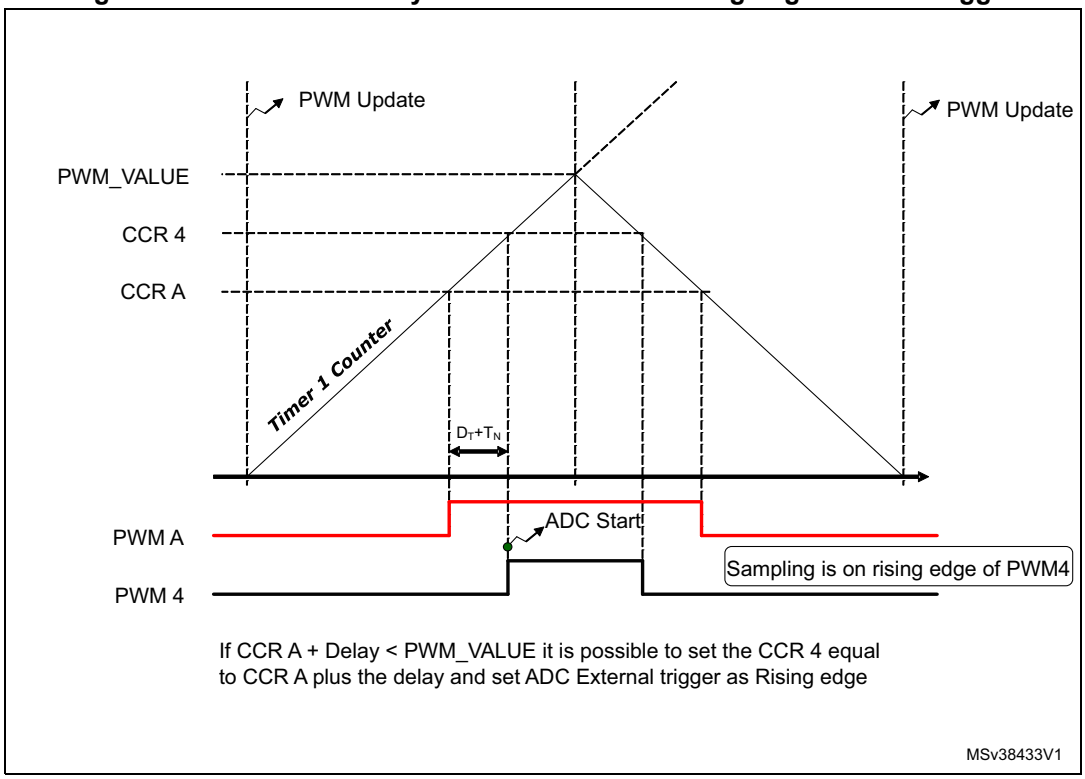
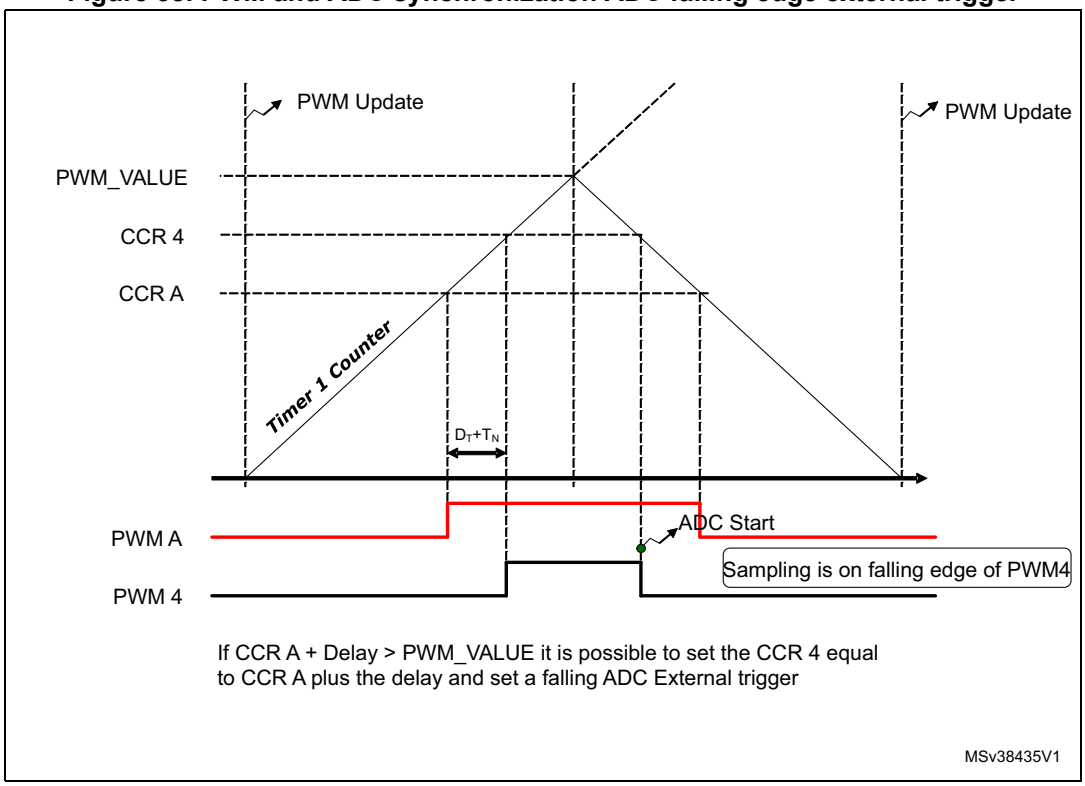

PWM Update
PWM Update
PWM_VALUE
CCR 4
CCR A
Timer 1 Counter
DT+TN
ADC Start
PWM A
PWM 4
Sampling is on rising edge of PWM4
If CCR A + Delay < PWM_VALUE it is possible to set the CCR 4 equal
to CCR A plus the delay and set ADC External trigger as Rising edge
MSv38433V1

Figure 38. PWM and ADC synchronization ADC falling edge external trigger


PWM Update
PWM Update
PWM_VALUE
CCR 4
CCR A
Timer 1 Counter
DT+TN
ADC Start
PWM A
PWM 4
Sampling is on falling edge of PWM4
If CCR A + Delay > PWM_VALUE it is possible to set the CCR 4 equal
to CCR A plus the delay and set a falling ADC External trigger
MSv38435V1

In this way, supposing that the sampling point must be set before the counter overflow, that is, when the TIM1 counter value matches the OCR4 register value during the up counting, the A/D conversion sequence for current sampling are started. If the sampling point must be set after the counter overflow, it's necessary set a falling edge ADC external trigger. Thus, when the TIM1 counter matches the OCR4 register value during the down counting, the A/D sampling are started.

After execution of the FOC algorithm, the value to be loaded into the OCR4 register is calculated to set the sampling point for the next PWM period, and the A/D converter is configured to sample the correct channels.

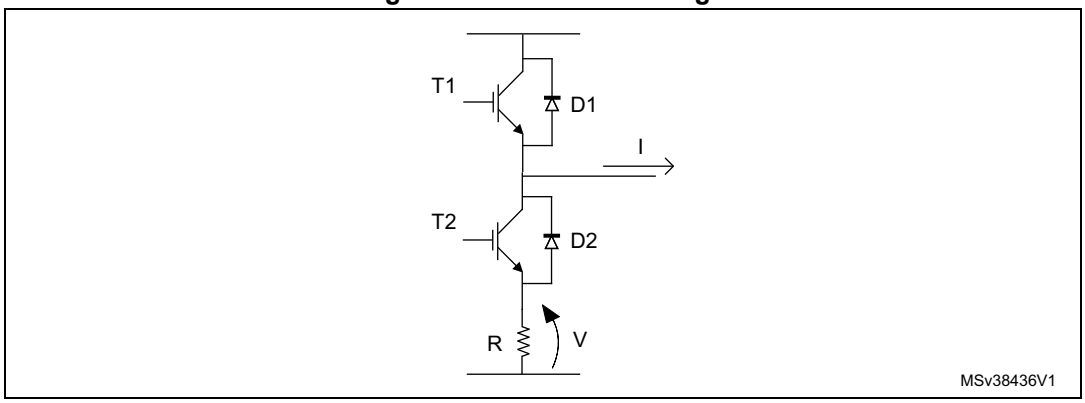
Table 5. Three-shunt current reading, used resources, single drive, STM32F302x6, STM32F302x8

Advanced Timer	ISR	ADC	Note
TIM1	ADC1_IRQn TIM1_BRK_TIM15_IRQN	ADC1	The dual drive mode and the internal PGA are not available

5.3 Current sampling in three-shunt topology using one A/D converter

Figure 39 shows one of the three inverter legs with the related shunt resistor.

Figure 39. three inverter legs



To indirectly measure the phase current I, it is possible to read the voltage V provided that the current flows through the shunt resistor, R.

It is possible to demonstrate that, whatever the direction of current I, it always flows through the resistor R if transistor T2 is switched on and T1 is switched off. This implies that, in order to properly reconstruct the current flowing through one of the inverter legs, it is necessary to properly synchronize the conversion start with the generated PWM signals. This also means that current reading cannot be performed on a phase where the duty cycle applied to the low side transistor is either null or very short.

As discussed in *Section 5.2*, to rebuild the currents flowing through a generic three-phase load, it is sufficient to sample only two out of three currents, the third one being computed from the relation given in *Section 5.2*. It is noted that two current samples are not simultaneous but the start of the second current sampling is delayed from the first current measurement by its global conversion time (Ts + Tc); this introduces a conceptual error in

the third current computation using the relation given in *Section 5.2*, because the two current samples are referred to two different time instants and this equation is true if the three current values are referred at the same time instant. Anyway, this error is negligible for a width range of motors.

Thus, depending on the space vector sector, the A/D conversion of voltage, V, will be performed only on the two phases where the duty cycles applied to the low side switches are the highest. Looking at the *Figure 19*, it can be noted that in the sectors 1 and 6, the voltage on phase A shunt resistor can be discarded; likewise in the sectors 2 and 3 for phase B, and in the sectors 4 and 5 for phase C.

Moreover, in order to have a correct A/D conversion of the two stator currents, it is necessary to distinguish between the different situations that can occur depending on PWM frequency and applied duty cycles.

Used symbols:

- DT is dead time.
- T_N is the duration of the noise induced on the shunt resistor voltage of a phase by the commutation of a switch belonging to another phase.
- T_R is the rising time of the input signal of the ADC.
- T_S is the sampling time of the Root part number 1 A/D.
- T_C is the conversion time of ADC. Refer to the STM32F30xx reference manual for more detailed information.

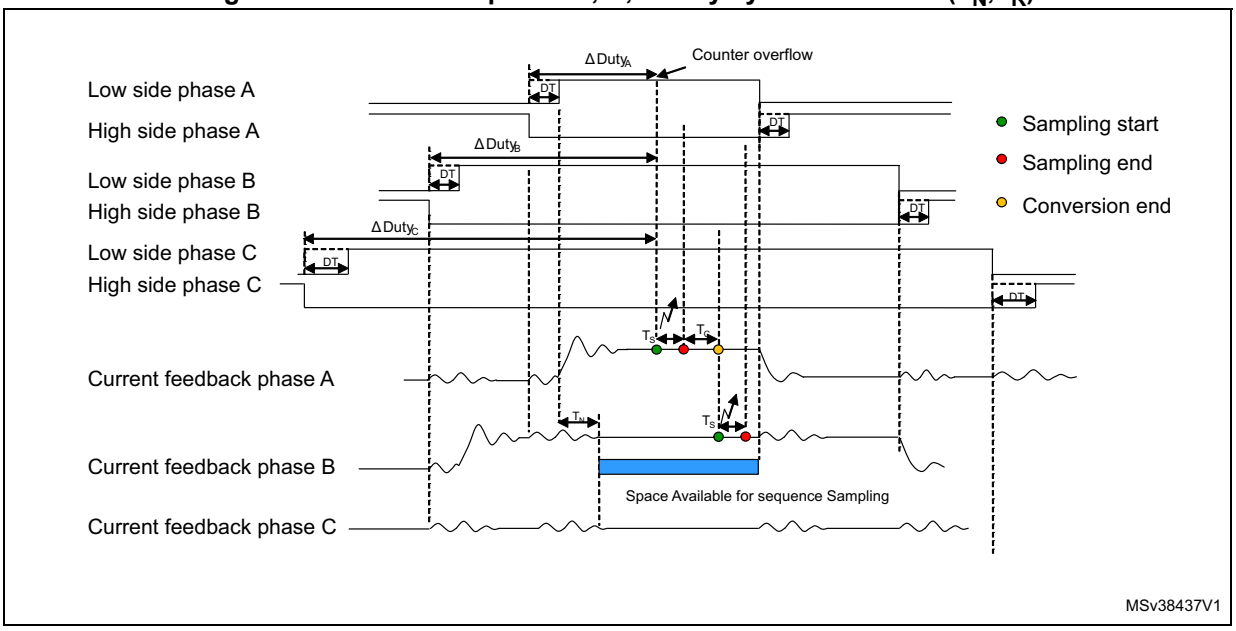
The following five cases are based on the hypothesis that $2T_S + T_C < DT + \max(T_N,T_R)$.

It's possible to individuate a common case for all sectors shown below.

Common Case: Duty cycles applied to Phases A, B, C low side switches are larger than $DT+ \max(T_N,T_R)$

In this case, to minimize measurement errors due to errors in calibration of the ADC, which introduce inaccuracies in the calculation of the third component by means of the equation $I_1 + I_2 + I_3 = 0$, always the currents of phases A and B are converted, as shown in the *Figure 40*.

Figure 40. Low side of phase A, B, C duty cycle > DT + max(T_N,T_R)



The following explanations refer to space vector sector 1 and can be applied in the same manner to the other sectors.

With the increase of the modulation index, $\Delta Duty_A$,$\Delta Duty_B$,$\Delta Duty_C$ can assume values smaller than DT+ max(T_N,T_R) and sampling in correspondence of the counter overflow can be impossible.

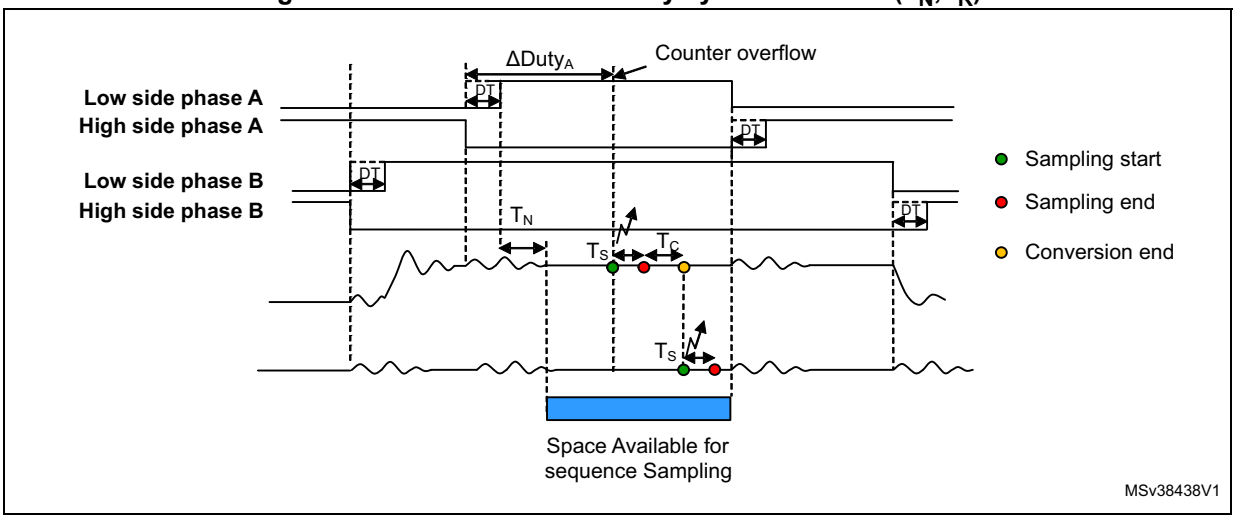
The following cases depend on the value of the minimum duty cycle of the low side signal between A, B, C phases. In the case of sector 1 is the Phase A as shown in *Figure 19*.

Case 1: Duty cycle applied to Phase A low side switch is larger than DT+ max(T_N,T_R)

This case typically occurs when SVPWM with low (<60%) modulation index is generated. The modulation index is the applied phase voltage magnitude expressed as a percentage of the maximum applicable phase voltage (the duty cycle ranges from 0% to 100%).

Figure 41 offers a reconstruction of the PWM signals applied to low side switches of phase A and B in these conditions, in addition of a view of the analog voltages measured on the ADC pins for both phase B and C.

Figure 41. Low side Phase A duty cycle > DT+ max(T_N,T_R)



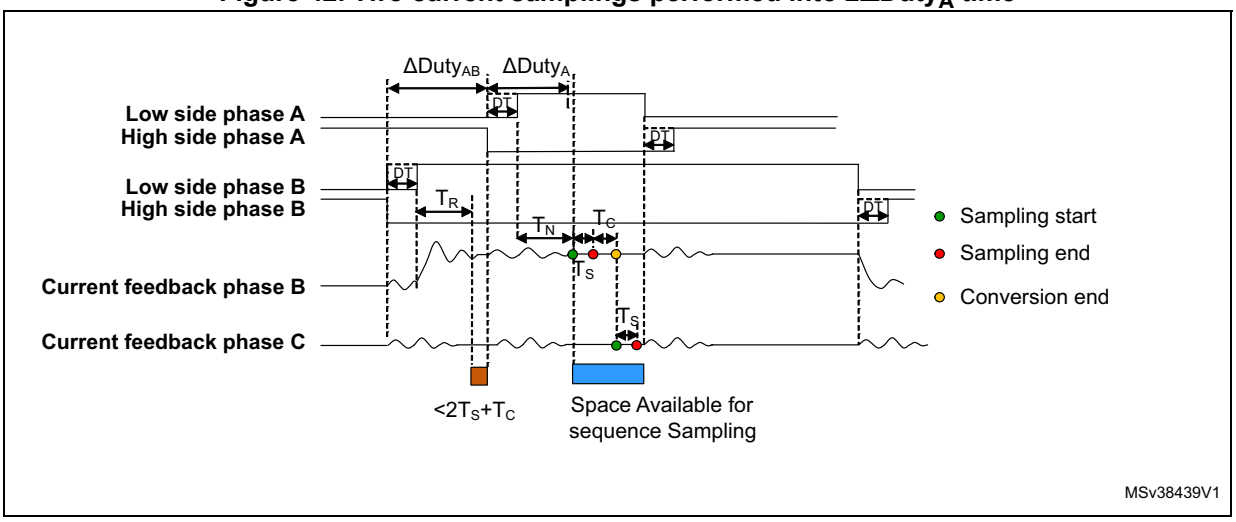
Case 2: $\Delta Duty_A$ < DT+ max(T_N,T_R) and $\Delta Duty_{AB}$ < 2 ($\Delta Duty_A$)

With the increase in modulation index, $\Delta Duty_A$ can assume values smaller than DT+ max(T_N,T_R). Start of conversion sequence synchronized with the counter overflow could be impossible.

In this case, the sequence of two currents can still be sampled between the two phase A low side commutations, but only after the counter overflow.

To avoid the acquisition of the noise induced on the phase B current feedback by phase A switch commutations, it is required to wait for the noise to be over (T_N). See Figure X7.

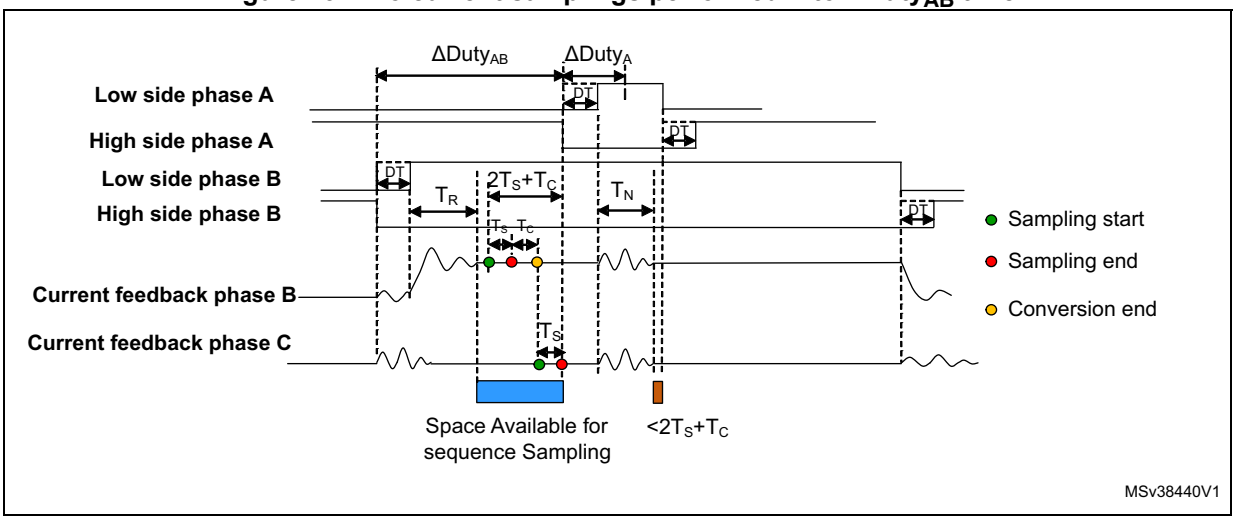
Figure 42. Two current samplings performed into 2$\Delta Duty_A$ time



Case 3: $\Delta Duty_A < DT + max(T_N,T_R)$ and $\Delta Duty_{AB} > 2 (\Delta Duty_A)$

In this case, it is no longer possible to sample the currents during phase A low-side on-state. Anyway, the two currents can be sampled between phase B low-side switch-on and phase A high-side switch-off. The choice was made to sample the currents (2TS + Tc) µs before of phase A high-side switch-off (see *Figure 43*)

Figure 43. Two current samplings performed into $\Delta Duty_{AB}$ time



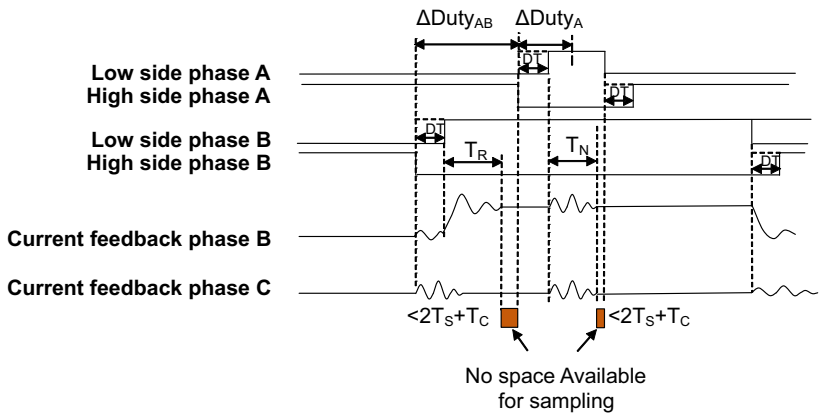
Case 4: $\Delta Duty_A < DT + max(T_N,T_R)$, $\Delta Duty_{AB} > 2 (\Delta Duty_A)$ and $\Delta Duty_{AB} - (DT + T_R) < 2T_N + T_R$)

In this case, the duty cycle applied to phase A is so short that no current sampling can be performed between the two low-side commutations considering that the two sampling are not simultaneous than the time requested to sampling is greater, because between the start of the two samplings there is the time of conversion of the first current.

If the difference in duty cycles between phase B and A is not long enough to allow the A/D conversions to be performed between phase B low-side switch-on and phase A high-side switch-off, it is impossible to sample the currents (See *Figure 44*).

To avoid this condition, it is necessary to reduce the maximum modulation index or to decrease the PWM frequency.

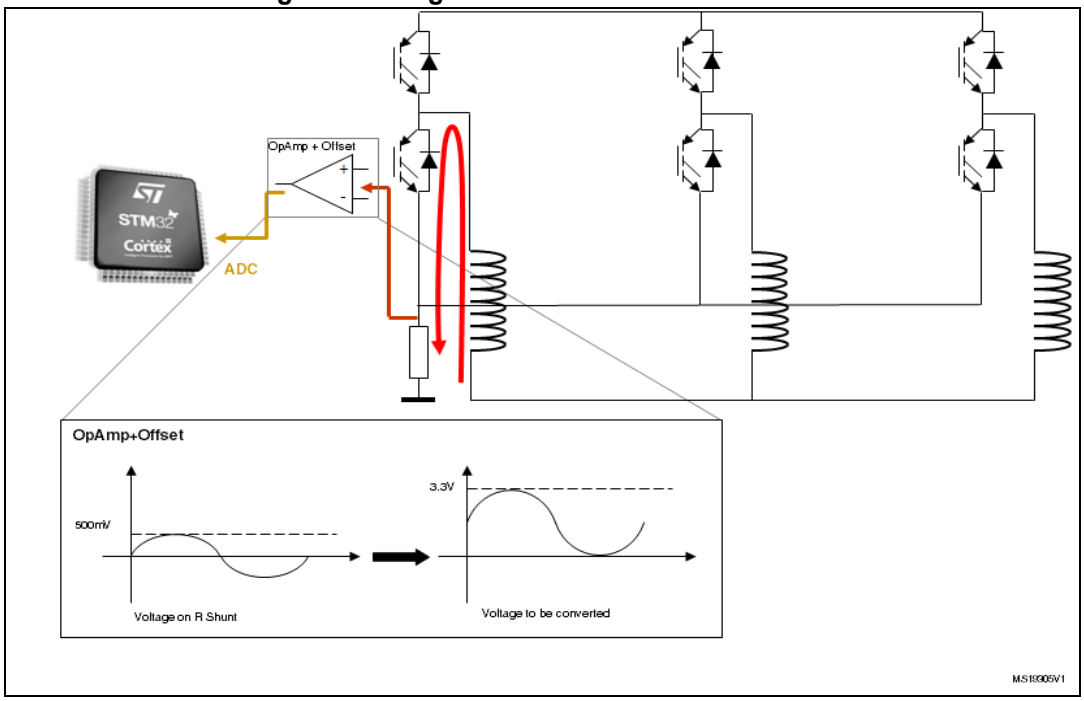
Figure 44. Two current samplings cannot performed



5.4 Current sampling in single-shunt topology

Figure 45 illustrates the single-shunt topology hardware architecture.

Figure 45. Single-shunt hardware architecture



It is possible to demonstrate that, for each configuration of the low-side switches, the current through the shunt resistor is given in *Table 6*. T_4, T_5 and T_6 assume the complementary values of T_1, T_2 and T_3, respectively.

In *Table 6*, value “0” means that the switch is open whereas value “1” means that the switch is closed.

Table 6. Current through the shunt resistor

T_1	T_2	T_3	I_{Shunt}
0	0	0	0
0	1	1	i_A
0	0	1	$-i_C$
1	0	1	i_B
1	0	0	$-i_A$
1	1	0	i_C
0	1	0	$-i_B$
1	1	1	0

Using the centered-aligned pattern, each PWM period is subdivided into 7 subperiods (see *Figure 46*). During three subperiods (I, IV, VII), the current through the shunt resistor is zero.

During the other subperiods, the current through the shunt resistor is symmetrical with respect to the center of the PWM.

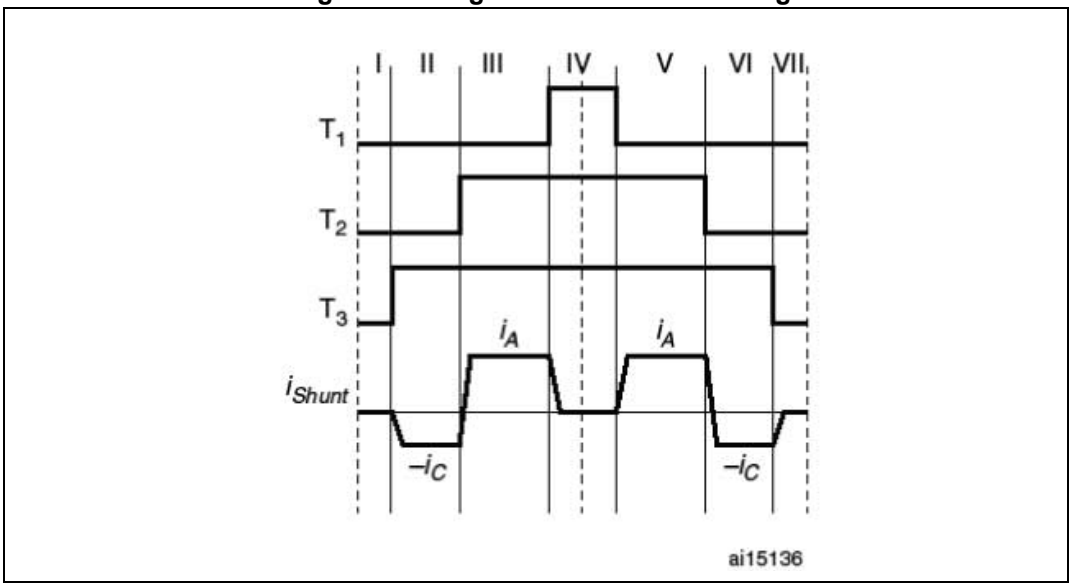
For the conditions showed in *Figure 46*, there are two pairs:

- subperiods II and VI, during which i_{Shunt} is equal to $-i_C$
- subperiods III and V, during which i_{Shunt} is equal to i_A

Under these conditions, it is possible to reconstruct the three-phase current through the motor from the sampled values:

- i_A is i_{Shunt} measured during subperiod III or V
- i_C is $-i_{Shunt}$ measured during subperiod II or VI
- $i_B = -i_A - i_C$

Figure 46. Single-shunt current reading



If the stator-voltage demand vector lies in the boundary space between two space vector sectors, two out of the three duty cycles will assume approximately the same value. In this case, the seven subperiods are reduced to five subperiods.

Under these conditions, only one current can be sampled, the other two cannot be reconstructed. This means that it is not possible to sense both currents during the same PWM period, when the imposed voltage demand vector falls in the gray area of the space vector diagram represented in *Figure 46*.

Table 7. Single-shunt current reading, used resources (single drive, F103/F100 LD/MD, F0x)

Adv. timer	Aux. timer	DMA	ISR	ADC	Note
TIM1	TIM3 (CH4)	DMA1_CH1 DMA1_CH3 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC1	F103/F100 LD device configuration, RC DAC cannot be used; ADC1 is used for general purpose conversions
TIM1	TIM4 (CH3)	DMA1_CH1 DMA1_CH5 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC1	F103/F100 MD device configuration; ADC1 is used for general purpose conversions
TIM1	TIM15 (CH1)	DMA1_CH2 DMA1_CH5 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC1	F051x device configuration
TIM1	TIM3 (CH4)	DMA1_CH2 DMA1_CH3 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC1	F050x/F030x device configuration

Table 8. single-shunt current reading, used resources (single or dual drive, F103HD)

Adv. timer	Aux. timer	DMA	ISR	ADC	Note
TIM1	TIM5 (CH4)	DMA1_CH1 DMA2_CH1 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC3	Option1: used by the first motor configured in single-shunt, or the second motor when the first is not single-shunt; ADC1 is used for general purpose conversions
TIM8	TIM4 (CH3)	DMA1_CH1 DMA1_CH5 DMA2_CH2	TIM8_UP DMA2_CH2_TC (Rep>1)	ADC1	Option1: used by the second motor configured in single-shunt when the first motor is also configured in single-shunt.
TIM8	TIM5 (CH4)	DMA1_CH1 DMA2_CH1 DMA2_CH2	TIM8_UP DMA2_CH2_TC (Rep>1)	ADC3	Option2: used by the first motor configured in single-shunt or by the second motor when the first is not single-shunt; ADC1 is used for general purpose conversions
TIM1	TIM4 (CH3)	DMA1_CH1 DMA1_CH5 DMA1_CH4	TIM1_UP DMA1_CH4_TC (Rep>1)	ADC1	Option2: used by the second motor configured in single-shunt when the first motor is also configured in single-shunt.

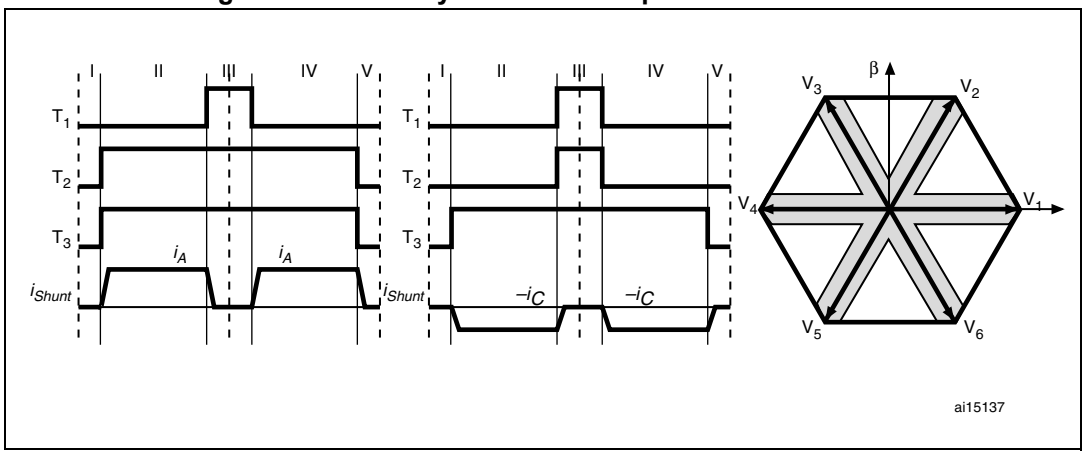
Table 9. Single-shunt current reading, used resources, single or dual drive, STM32F2xxx/F4xx

Adv Timer	Aux Timer	DMA	ISR	ADC	Note
TIM1	TIM5 (ch4)	DMA1, stream1, ch6; DMA2, stream4, ch6	TIM1_UP; DMA2_stream4_TC (FOC rate>1)	ADC3	Option 1: used by first motor when it is configured in single shunt, or by second motor when the first one isn't in single shunt. ADVC1 used for general purpose conversions
TIM8	TIM4(ch2)	DMA1, stream3,ch2; DMA2, stream7, ch7	TIM8_UP; DMA2_stream7_TC (FOC rate>1)	ADC1	Option 1: used by second motor when it is configured in single shunt and when first motor isn't in single shunt. ADVC1 used for general purpose conversions
TIM8	TIM5(ch4)	DMA1, stream1,ch6; DMA2, stream7, ch7	TIM8_UP; DMA2_stream7_TC (FOC rate>1)	ADC3	Option 2: used by first motor when it is configured in single shunt, or by second motor when the first one isn't in single shunt. ADVC1 used for general purpose conversions
TIM1	TIM4(ch2)	DMA1, stream3,ch2; DMA2, stream4, ch6	TIM1_UP; DMA2_stream4_TC (FOC rate>1)	ADC1	Option 2: used by second motor when it is configured in single shunt and when first motor is also in single shunt. ADVC1 used for general purpose conversions

Using F103HD, F2xx, F4xx in single drive, it is possible to choose between option 1 and option 2 (*Table 8* and *Table 9*); resources are allocated or saved accordingly.

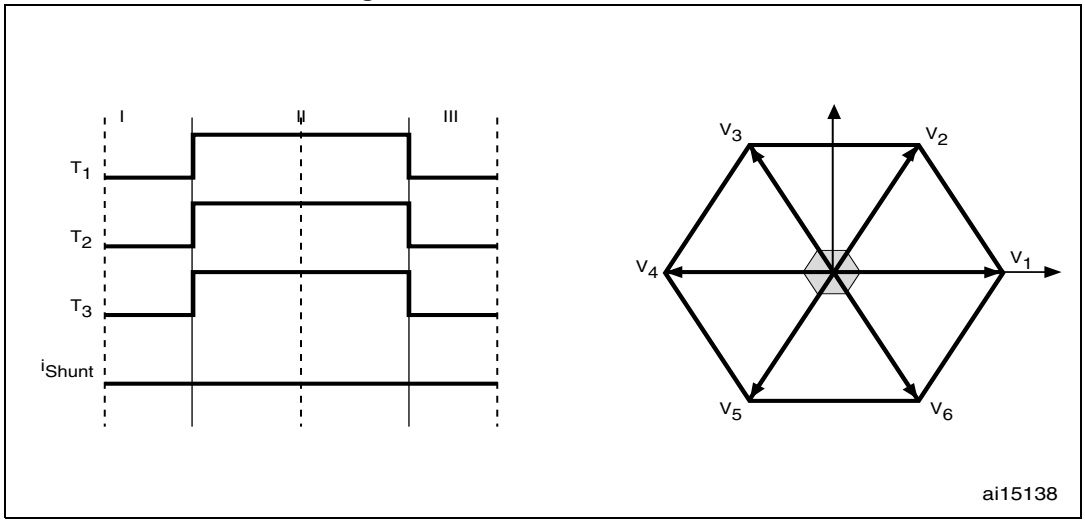
Please refer to *Section 6: Current sensing and protection on embedded PGA* for STM32F30x microcontroller configuration.

Figure 47. Boundary between two space-vector sectors



Similarly, for a low modulation index, the three duty cycles assume approximately the same value. In this case, the seven subperiods are reduced to three subperiods. During all three subperiods, the current through the shunt resistor is zero. This means that it is not possible to sense any current when the imposed voltage vector falls in the gray area of the space-vector diagram represented in *Figure 48*.

Figure 48. Low modulation index



5.4.1 Definition of the noise parameter and boundary zone

T_{Rise} is the time required for the data to become stable in the ADC channel after the power device has been switched on or off.

The duration of the ADC sampling is called the sampling time.

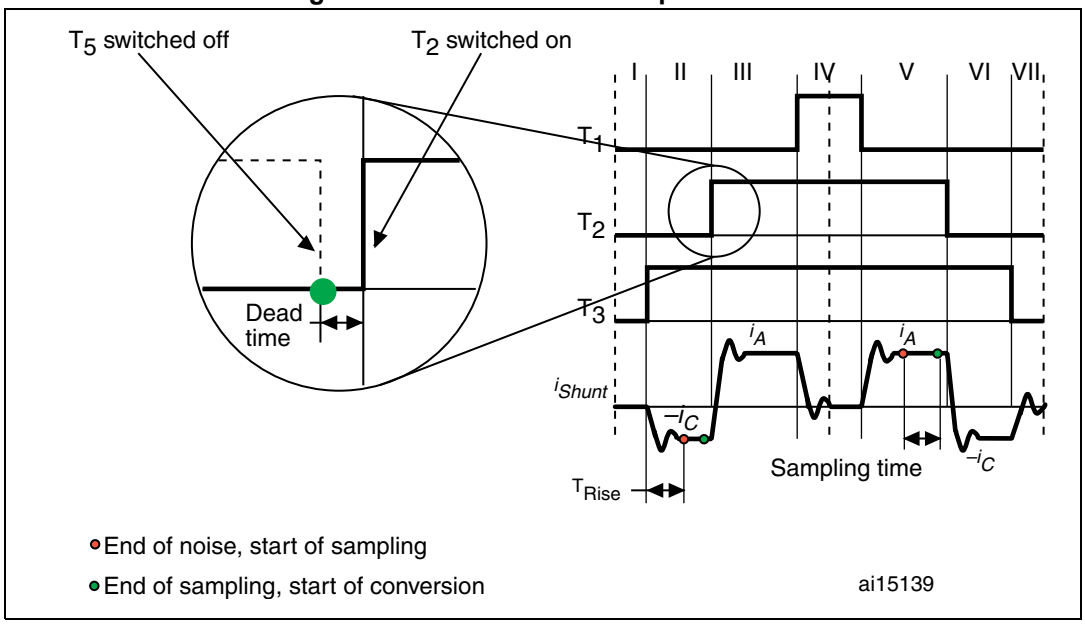
T_{MIN} is the minimum time required to perform the sampling, and

$T_{MIN} = T_{Rise}$ + sampling time + dead time

D_{MIN} is the value of T_{MIN} expressed in duty cycle percent. It is related to the PWM frequency as follows:

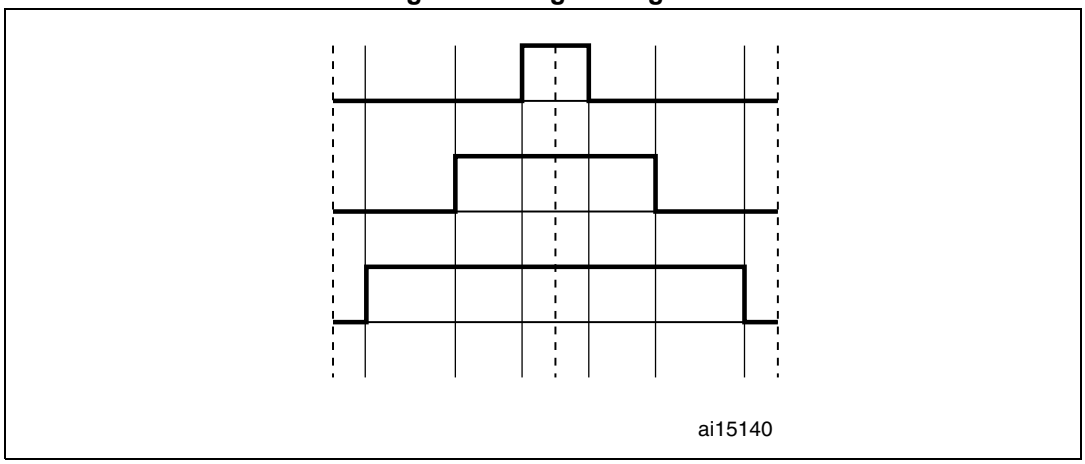
$D_{MIN} = (T_{MIN} \times F_{PWM}) \times 100$

Figure 49. Definition of noise parameters



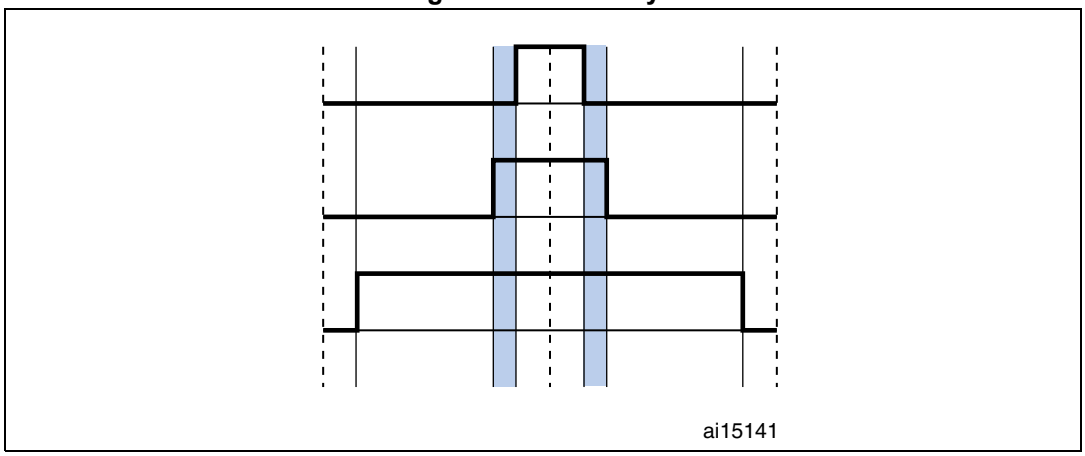
The voltage-demand vector lies in a region called the Regular region when the three duty cycles (calculated by space vector modulation) inside a PWM pattern differ from each other by more than D_{MIN}. This is represented in *Figure 50*.

Figure 50. Regular region



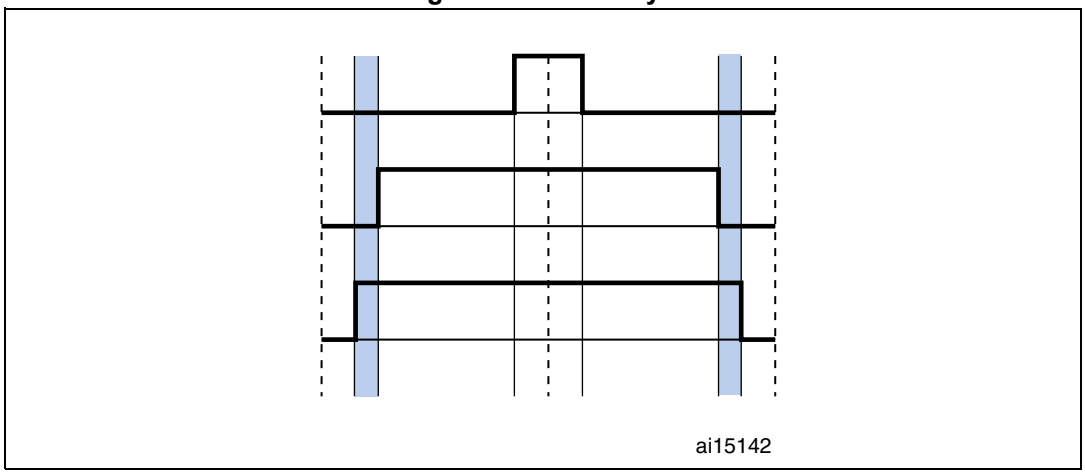
The voltage-demand vector lies in a region called Boundary 1 when two duty cycles differ from each other by less than D_{MIN}, and the third is greater than the other two and differs from them by more than D_{MIN}. This is represented in *Figure 51*.

Figure 51. Boundary 1



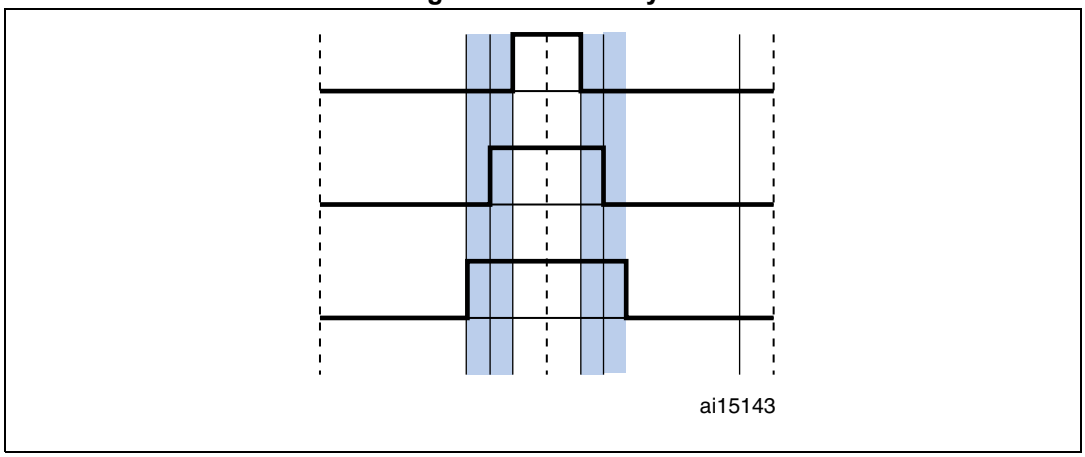
The voltage-demand vector lies in a region called Boundary 2 when two duty cycles differ from each other by less than D_{MIN}, and the third is smaller than the other two and differs from them by more than D_{MIN}. This is represented in *Figure 52*.

Figure 52. Boundary 2



The voltage-demand vector lies in a region called Boundary 3 when the three PWM signals differ from each other by less than D_{MIN}. This is represented in *Figure 53*.

Figure 53. Boundary 3



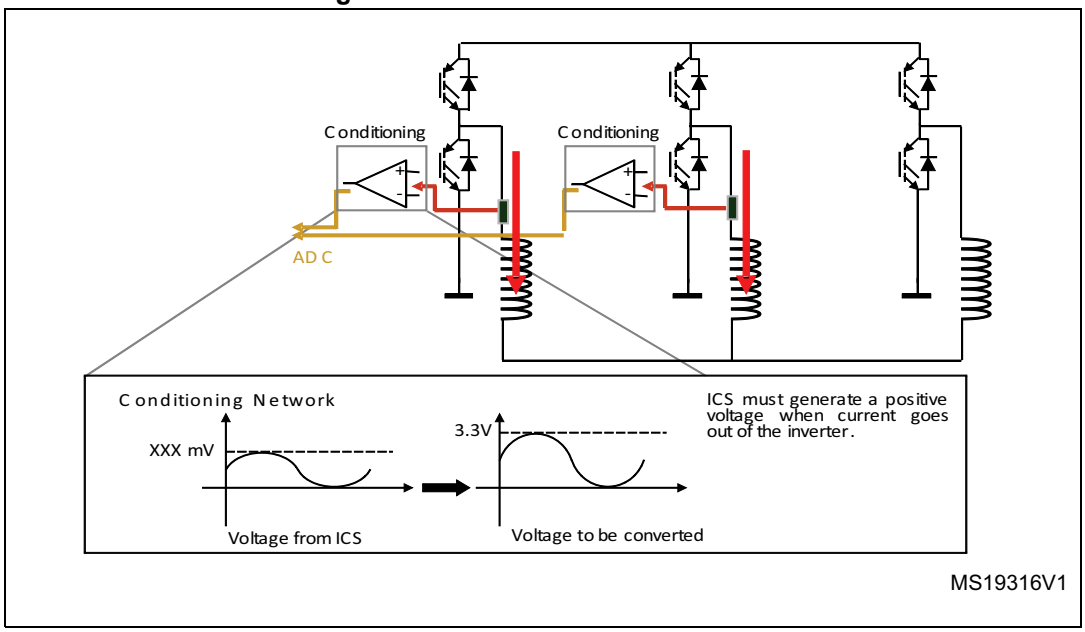
If the voltage-demand vector lies in Boundary 1 or Boundary 2 region, a distortion must be introduced in the related PWM signal phases to sample the motor phase current.

An ST patented technique for current sampling in the “Boundary” regions has been implemented in the firmware. Please contact your nearest ST sales office or support team for further information about this technique.

5.5 Current sampling in isolated current sensor topology

Figure 54 illustrates the ICS topology hardware architecture.

Figure 54. ICS hardware architecture



The three currents I_1, I_2, and I_3 flowing through a three-phase system follow the mathematical relationship:

$$I_1 + I_2 + I_3 = 0$$

Table 10. ICS current reading, used resources (single drive, F103 LD/MD)

Adv. timer	DMA	ISR	ADC master	ADC slave	Note
TIM1	DMA1_CH5	None	ADC1	ADC2	DMA is used to enable ADC injected conversion external trigger. Disabling is performed by software.

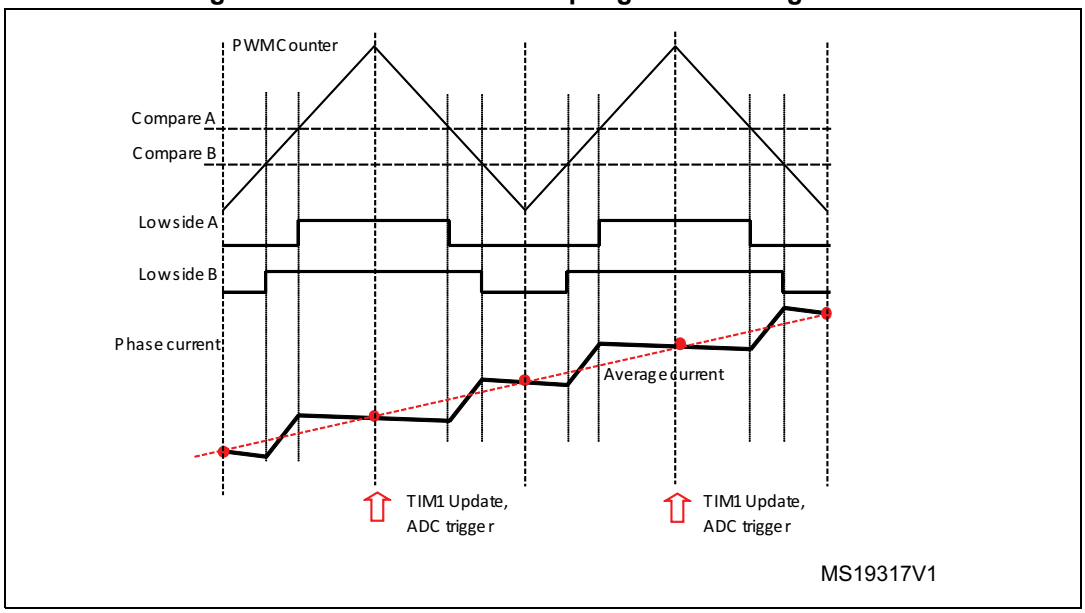
Table 11. ICS current reading, used resources (single or dual drive, F103 HD, F2xx, F4xx)

Adv. timer	DMA	ISR	ADC	Note
TIM1	None	TIM1_UP	ADC1 ADC2	Used by the first or second motors configured in three-shunt, depending on the user selection. ADC is used in time sharing. Trigger selection is performed in the TIM_UP ISR.
TIM8	None	TIM8_UP	ADC1 ADC2	Used by the first or second motor configured in three-shunt, depending on the user selection. ADC is used in time sharing. Trigger selection is performed in the TIM_UP ISR.

Therefore, to reconstruct the currents flowing through a generic three-phase load, it is sufficient to sample only two out of the three currents while the third one can be computed by using the above relationship.

The flexibility of the Root part number 1 A/D converter trigger makes it possible to synchronize the two A/D conversions necessary for reconstructing the stator currents flowing through the motor with the PWM reload register updates. This is important because, as shown in *Figure 55*, it is precisely during the counter overflow and underflow that the average level of current is equal to the sampled current. Refer to the Root part number 1 reference manual to learn more about A/D conversion triggering.

Figure 55. Stator currents sampling in ICS configuration



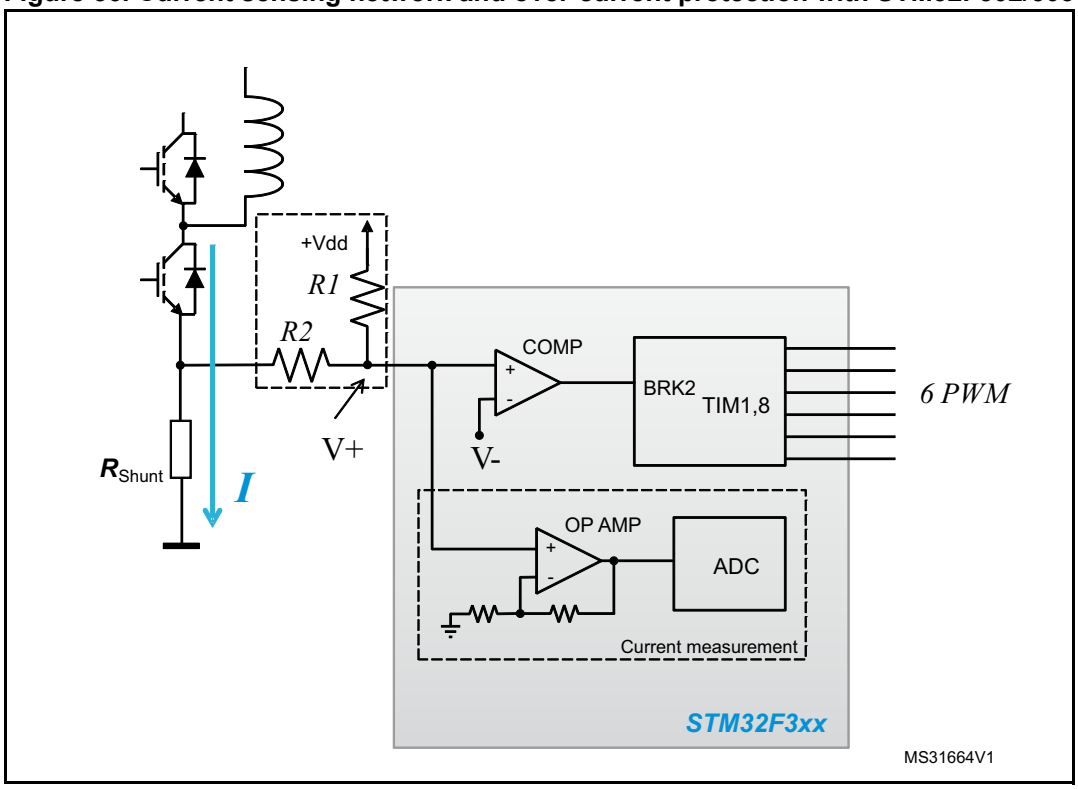
6 Current sensing and protection on embedded PGA

6.1 Introduction

The STM32F302xB/C or STM32F303xB/C microcontrollers feature an enhanced set of peripherals including comparators, PGAs, DACs and high-speed ADCs. This section describes how to use these peripherals according to what is made available by the MC library.

Figure 56 shows a current sensing and over-current protection scheme that can be implemented using the internal resources of the STM32F302/303. The voltage drop on the shunt resistor, due to the motor phase current, can be either positive or negative, an offset is set by R1 and R2. The signal is linked to a microcontroller input pin that has both functionality of amplifier and comparator non-inverting.

Figure 56. Current sensing network and over-current protection with STM32F302/303



This optimized configuration, using STM32F3, reduces the number of external component used and also microcontroller's pins assigned to the MC application.

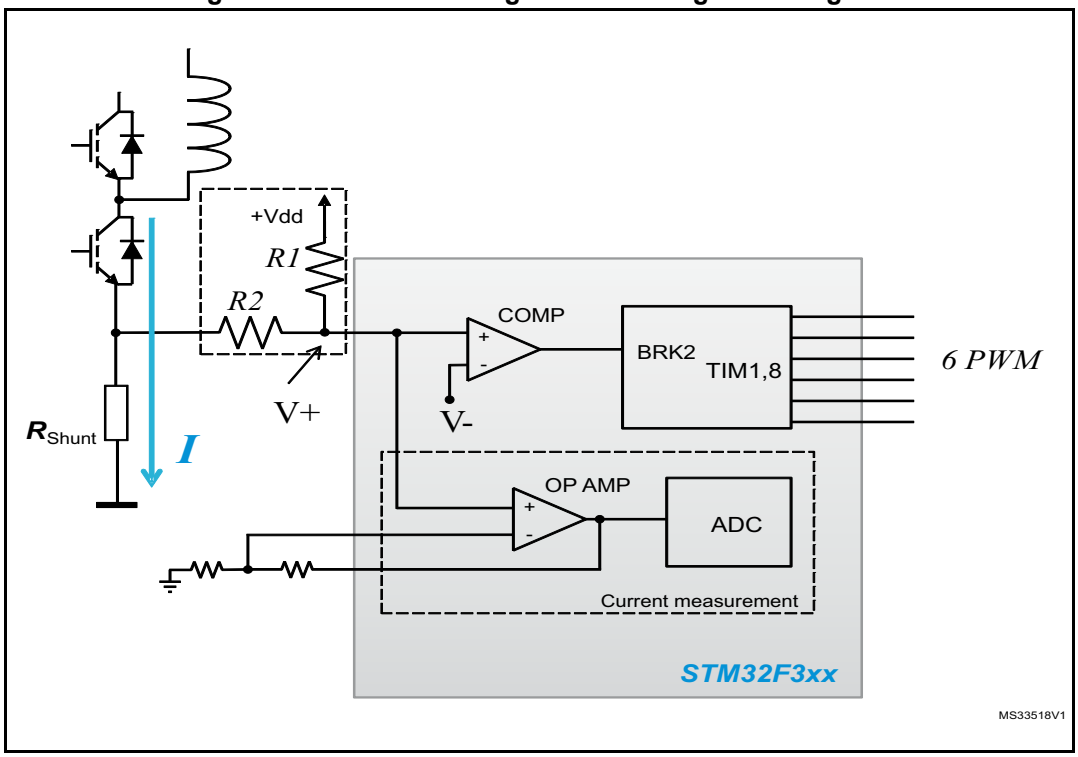
6.2 Current sensing

In order to maximize the resolution of the measurement, the PGA can be used to adapt the level of voltage drop in the shunt resistor (Rshunt), caused by the motor current, up to the maximum range allowed by the analog to digital converter (ADC).

The PGA has a set of fixed internal gains (x2, x4, x8, x16). An alternative option in PGA mode allows you to route the central point of the resistive network on one of the I/Os connected to the non-inverting input. This feature can be used for instance to add a low-pass filter to PGA, as shown in *Figure 57*.

On the other hand, if a different value of amplification is required, it is possible to define the amplification network (for instance as it's shown in *Figure 56*).

Figure 57. Current sensing network using external gains

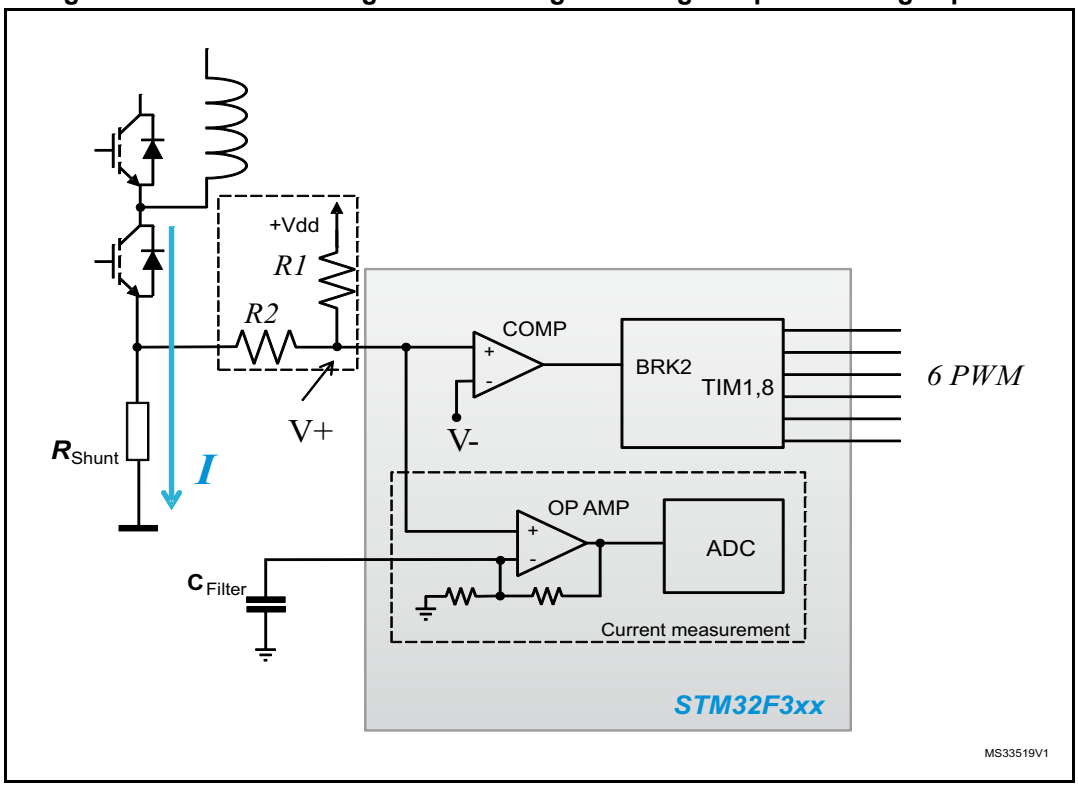


The MC library can be arranged to match all the configurations shown. In the dialogue window located in Control Stage -> Analog Input -> Phase current feedback (*Figure 59*), setting:

- “Embedded PGA" as current sensing topology;
- "PGA internal gain (like in *Figure 56*): Settling "Internal" in the "OPAMP Gain" drop down list;
- "PGA external gain (like in *Figure 57*): Settling "External" in the "OPAMP Gain" drop down list;
- "PGA internal gain with external filtering capacitor (like in *Figure 58*): Settling "Internal" in the "OPAMP Gain" drop down list and checking the "Feedback net filtering" check box in the same group.

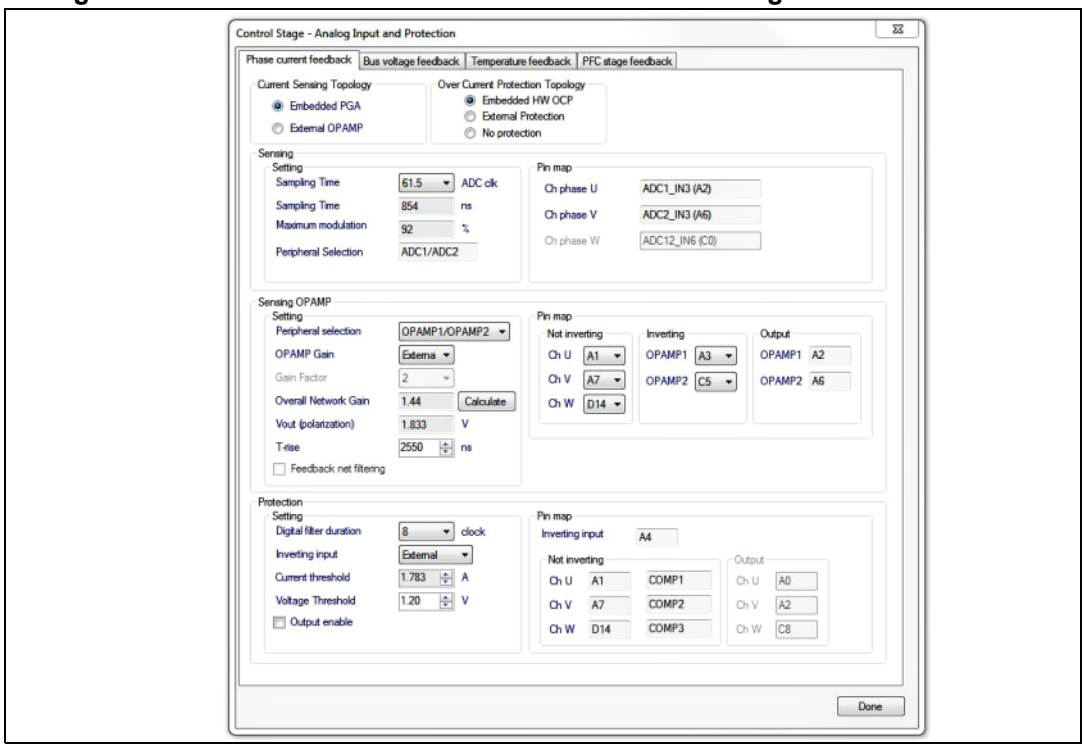
Just one of this setting is present in the workbench for each drives, since the configuration applies to each shunt resistor conditioning network.

Figure 58. Current sensing network using internal gains plus filtering capacitor



On the other hand, it is possible to setup the motor current measurement network to use external operational amplifiers. In this case the amplified signals are directly fed to the ADC channels. In the dialogue window located in Control Stage -> Analog Input -> Phase current feedback, setting "External OPAMP" as current sensing topology.

Figure 59. STMCWB window related to PGA/COMP settings for motor currents



6.3 Overcurrent protection

The basic principle of the hardware over-current protection mechanism can be summarized as follows:

- The phase current of the motor flows in the power transistor of the inverter bridge and passes through the shunt resistor (RShunt) producing a voltage drop (V+).
- This voltage drop is compared with a threshold (V-) defining the maximum admissible current.
- If the threshold is exceeded, a break signal stops the PWM generation putting the system in a safe state.

All of these actions can be performed using the internal resources of the STM32F302/303 and, in particular, the embedded comparators and the advanced timer break function (BRK2). As shown in *Figure 56*, *Figure 57* and *Figure 58* the same signal is fed to both not inverting input of embedded comparators and PGA.

The overcurrent threshold (V-) can be defined in three different ways:

- using one of the available internal voltage reference (1.2V, 0.9V, 0.6V, 0.3V);
- providing it externally using the inverting input pin of the comparator;
- programming a DAC channel.

The MC library can be arranged to match all the configurations shown by using the ST MC Workbench, creating a project based on STM32F302xB/C or STM32F303xB/C, from the dialogue window located in Control Stage -> Analog Input -> Phase current feedback

(*Figure 59*), setting:

- “Embedded HW OCP" radio button as overcurrent protection topology;
- HW OCP internal threshold: selecting "Internal" in the "Inverting input" drop down list and choosing the internal voltage reference (among available values) in "Voltage Threshold".
- HW OCP external threshold: selecting "External" in the "Inverting input" drop down list and editing the external voltage reference in "Voltage Threshold".
- HW OCP internal threshold using DAC: selecting "DAC" in the "Inverting input" drop down list and editing the DAC voltage reference to be generated in "Voltage Threshold". A DAC channel must be assigned for this functionality (OCP) from the related dialogue window located in Control stage -> DAC functionality (*Figure 62*).

On the other hand, it is possible to setup the motor overcurrent protection network to use external components. In this case the overcurrent protection signal - coming from a comparator for instance - is directly fed to the advanced-timer's BKIN2 pin. By using the ST MC Workbench, creating a project based on STM32F302 or STM32F303, from the dialogue window located in Control Stage -> Analog Input -> Phase current feedback, setting "External protection" as OCP protection topology.

In any case, either using embedded comparators or external components, a digital filter, upstream the BKIN2 function, can be enabled and configured to reject noises.

6.4 Resources allocation - single drive

For project based on STM32F302xB/C or STM32F303xB/C the current feedback network configurations supported by STM32 FOC SDK are single shunt and three shunt.

6.4.1 Single shunt topology

According to configuration (as explained in *Section 6.2: Current sensing* and *Section 6.3: Overcurrent protection*), one ADC, OPAMP, comparator, DAC channel must be assigned.

- If "Embedded PGA" is enabled, the selection of ADC peripheral (and input pin) is linked to this specific PGA peripheral.
- If "Embedded HW OCP" and "Embedded PGA" are enabled, the selection of ADC and comparator (and their input and '+" pins) is linked to to this specific PGA peripheral (and its '+' input).
- If "Embedded HW OCP" is enabled and "Embedded PGA" is disabled, the selection of comparator is free.
- If "Embedded HW OCP" and "Embedded PGA" are both disabled, the selection of comparator and ADC is free.
- If both PGA and comparator for OC protection are used they will share the same input pins for the motor current measurement signal.

6.4.2 Three shunts topology

According to configuration (as explained in *Section 6.2: Current sensing* and *Section 6.3: Overcurrent protection*), 2 ADCs, 2 OPAMPs, 3 comparators, 1 DAC channel must be assigned.

- If "Embedded PGA" is enabled, the selection of ADC peripherals (and input pins) is linked to this specific PGA peripherals.
- If "Embedded HW OCP" and "Embedded PGA" are enabled, the selection of ADCs and comparators (and their inputs and '+" pins) is linked to this specific PGA peripherals (and theirs '+' inputs).
- If "Embedded HW OCP" is enabled and "Embedded PGA" is disabled, the selection of comparators is free.
- If "Embedded HW OCP" and "Embedded PGA" are both disabled, the selection of comparators and ADCs is free.
- The pair OPAMP1/OPAMP2 can be used in a project based on STM32F302 or STM32F303; the pair OPAMP3/OPAMP4 can be used additionally in a project based on STM32F303.
- The pair ADC1/ADC2 can be used in a project based on STM32F302 or STM32F303; the pair ADC3/ADC4 can be used additionally in a project based on STM32F303.
- If both PGA and comparator for OC protection are used they will share the same input pins for the motor current measurement signal.

6.5 Resources allocation - dual drive

Dual drive project can be designed by using a STM32F303 microcontroller. The current feedback network configurations supported by STM32 FOC SDK are single shunt and three shunt.

Dual single shunt drive, dual three shunts drive and mixed "single plus three" shunts drives are allowed.

The sharing of peripherals between "single shunt drive" and "three shunt drive" is not allowed.

The sharing of peripherals between two "single shunt drive" is not allowed.

The sharing of peripherals between two "three shunt drive" is allowed, in the forms expressed below.

6.5.1 Single shunt topology

For each motor, according to configuration (as explained in *Section 6.2: Current sensing* and *Section 6.3: Overcurrent protection*), one ADC, OPAMP and comparator must be assigned.

- If "Embedded PGA" is enabled, the selection of ADC peripheral (and input pin) is linked to this specific PGA peripheral.
- If "Embedded HW OCP" and "Embedded PGA" are enabled, the selection of ADC and comparator (and their input and '+" pins) is linked to this specific PGA peripheral (and its '+' input).
- If "Embedded HW OCP" is enabled and "Embedded PGA" is disabled, the selection of comparator is free.
- If "Embedded HW OCP" and "Embedded PGA" are both disabled, the selection of comparator and ADC is free.
- If both PGA and comparator for OC protection are used they will share the same input pins for the motor current measurement signal.

6.5.2 Three shunts topology mixed with Single shunt topology

According to configuration (as explained in *Section 6.2: Current sensing* and *Section 6.3: Overcurrent protection*), 2 ADCs, 2 OPAMPs, 3 comparators, 1 DAC channel must be assigned.

- If "Embedded PGA" is enabled, the selection of ADC peripherals (and input pins) is linked to this specific PGA peripherals.
- If "Embedded HW OCP" and "Embedded PGA" are enabled, the selection of ADCs and comparators (and their inputs and '+" pins) is linked to this specific PGA peripherals (and theirs '+' inputs).
- If "Embedded HW OCP" is enabled and "Embedded PGA" is disabled, the selection of comparators is free.
- If "Embedded HW OCP" and "Embedded PGA" are both disabled, the selection of comparators and ADCs is free.
- The pair OPAMP1/OPAMP2 can be used in a project based on STM32F302 or STM32F303; the pair OPAMP3/OPAMP4 can be used additionally in a project based on STM32F303.
- The pair ADC1/ADC2 can be used in a project based on STM32F302 or STM32F303; the pair ADC3/ADC4 can be used additionally in a project based on STM32F303.
- If both PGA and comparator for OC protection are used they will share the same input pins for the motor current measurement signal.

6.5.3 Dual Three shunts topology, not shared resources

According to configuration (as explained in *Section 6.2: Current sensing* and *Section 6.3: Overcurrent protection*), 4 ADCs, 4 OPAMPs, 6 comparators, 2 DAC channels must be assigned.

- If "Embedded PGA" is enabled, the selection of ADC peripherals (and input pins) is linked to this specific PGA peripherals.
- If "Embedded HW OCP" and "Embedded PGA" are enabled, the selection of ADCs and comparators (and their inputs and '+" pins) is linked to this specific PGA peripherals (and theirs '+' inputs).
- If "Embedded HW OCP" is enabled and "Embedded PGA" is disabled, the selection of comparators is free.
- If "Embedded HW OCP" and "Embedded PGA" are both disabled, the selection of comparators and ADCs is free.
- The pairs that can be used are OPAMP1/OPAMP2 can be used in a project based on STM32F302 or STM32F303; the pair OPAMP3/OPAMP4 can be used additionally in a project based on STM32F303.
- The pair ADC1/ADC2 can be used in a project based on STM32F302 or STM32F303; the pair ADC3/ADC4 can be used additionally in a project based on STM32F303.
- If both PGA and comparator for OC protection are used they will share the same input pins for the motor current measurement signal.

6.5.4 Dual Three shunts topology, shared resources

If both drives are three shunts, it can be possible to share the ADC and/or the PGA to perform the motor current measurement. To do this is mandatory to have both use external operational amplifier or both use the embedded PGA for the motor current measurement signals amplification. It can be settled by the user in the ST MC Workbench clicking the "Shared resource" check box in the Control Stage -> Analog Input.

If shared resource is settled and external operational amplifier is used, it is possible to use the pairs ADC1/ADC2 or the pairs ADC3/ADC4 for both drivers. ST MC Workbench will propose the allowed inputs pins for motor currents measurement in this case.

If shared resource is settled and embedded PGA is used, the following configuration is used:

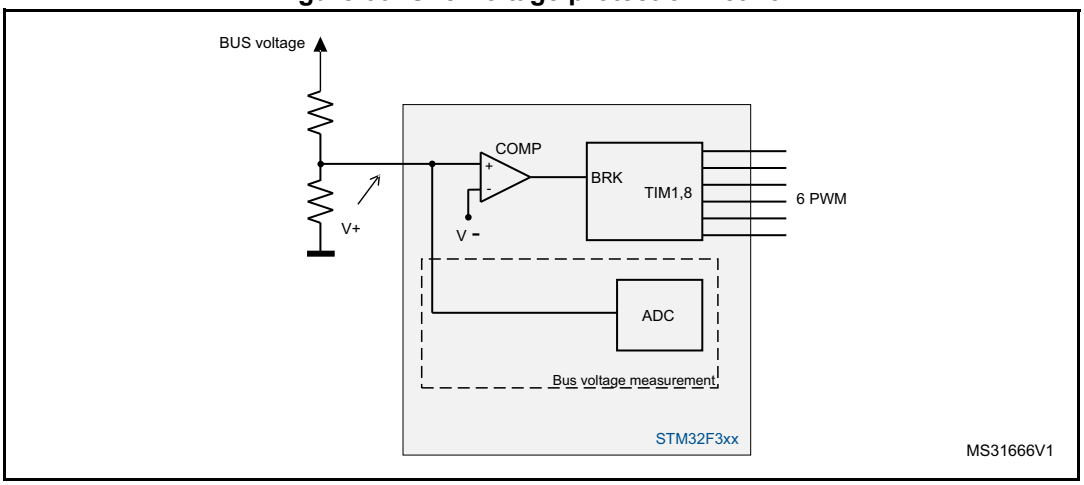
- The pair OPAMP1/OPAMP3 is used,
- OPAMP gains is only "Internal",
- External capacitor filer is not allowed,
- Input pins are: PA5, PA7, and PB13 respectively U, V, W for motor 1 and PA1, PA3 and PB0 respectively U, V, W for motor 2.

In this case, if the hardware over current protection is managed by internal comparators, is mandatory to connect externally the pins PA3 with one of the pins PB14 or PD14 and connect externally the pins PA5 with one of the pins PB11 or PD11. The pins selected can be settled in the workbench in Control Stage -> Analog Input -> Phase current feedback -> Protection.

7 Overvoltage protection with embedded analog (STM32F3x only)

Figure 60 shows a basic implementation of over-voltage protection network that can be implemented using the internal resources of the STM32F30x.

Figure 60. Overvoltage protection network



The principle is similar to the one described in *Section 6.3: Overcurrent protection*:

- A resistive voltage divider provides a signal proportional to the bus voltage. It must be sized depending on the bus voltage range requested by the target application, so that is never exceeds the MCU's input maximum admissible voltage level.
- This reading is compared to an over-voltage threshold to generate a fault signal.
- If the threshold is exceeded, a break signal stops the PWM generation putting the system in a safe state.

As mentioned before, these actions can be performed automatically using the internal comparator of the STM32F30x. In this case, it is convenient to use the second break functionality (BRK) of the advanced timer in order to differentiate the action to perform on the PWM signals in case of an over-current: disable PMW generation or turn-on low side switches.

The MC library can be arranged to match these configurations by using the ST MC Workbench, creating a project based on STM32F302 or STM32F303, from the dialogue window located in Control Stage -> Analog Input -> Bus voltage feedback (*Figure 61*), setting:

- "Embedded HW OVP" checkbox;
- HW OVP internal threshold: selecting "Internal" in the "Inverting input" drop down list and choosing the internal voltage reference (among available values) in "Comparator Input".
- HW OVP external threshold: selecting "External" in the "Inverting input" drop down list and editing the external voltage reference in "Comparator Input".
- HW OVP internal threshold using DAC: selecting "DAC" in the "Inverting input" drop down list and editing the DAC voltage reference to be generated in "Comparator Input". A DAC channel must be assigned for this functionality (OVP) from the related dialogue

window located in Control stage -> DAC functionality (*Figure 62*)

- The selection of 'not-inverting' input pin contextually picks the comparator to be used.
- The drive behavior when an overvoltage state is found: disable PWM generation, or turn-on low side switches;

Enabling or disabling the comparator output has no effect on the overvoltage protection functionality itself

Figure 61. STMCWB windows related to ADC/COMP settings for DC bus Voltage

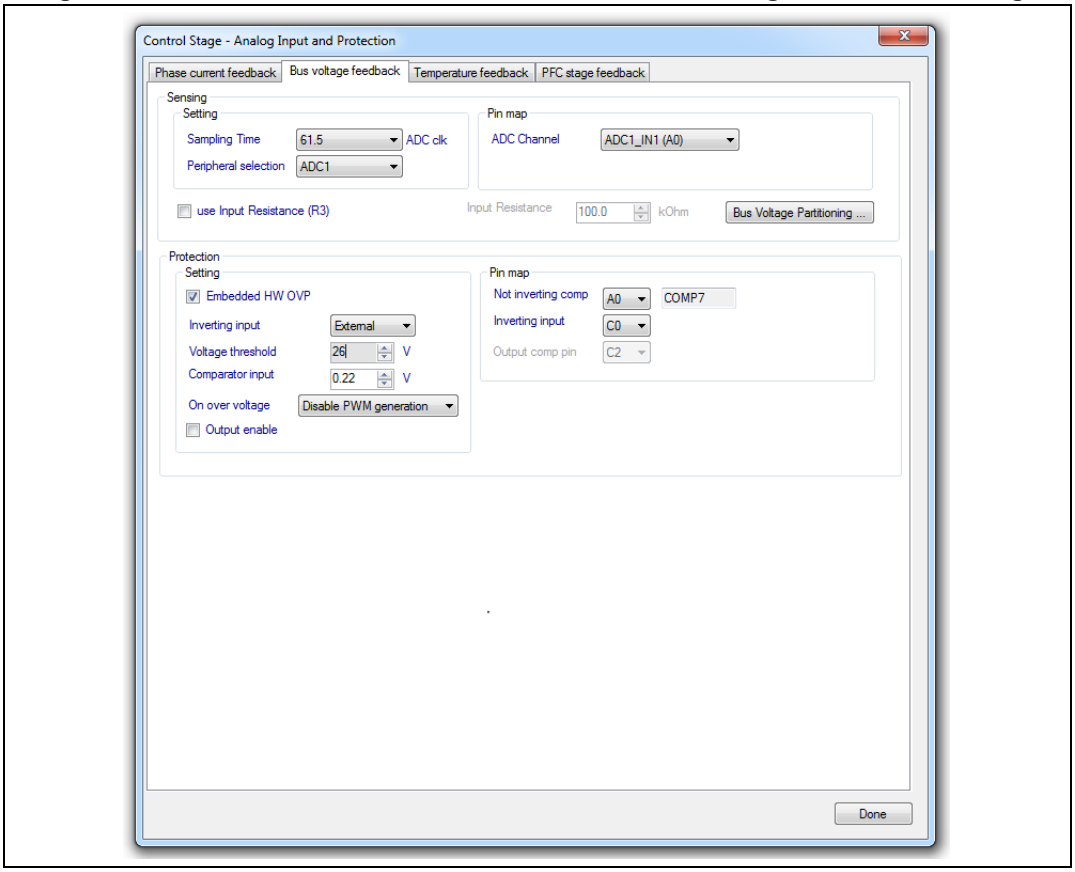
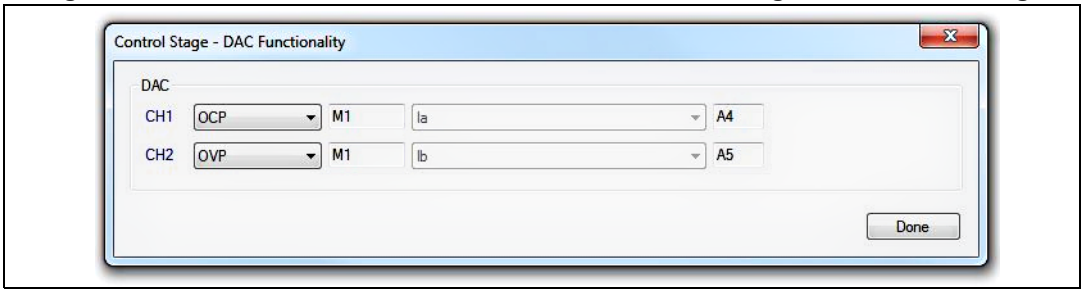


Figure 62. STMCWB windows related to ADC/COMP settings for DC bus Voltage



8 Rotor position/speed feedback

Section 4.3: Introduction to the PMSM FOC drive shows that rotor position/speed measurement has a crucial role in PMSM field-oriented control. Hall sensors or encoders are broadly used in the control chain for that purpose. Sensorless algorithms for rotor position/speed feedback are considered very useful for various reasons: to lower the overall cost of the application, to enhance the reliability by redundancy, and so on. Refer to *Section 8.1: Sensorless algorithm (BEMF reconstruction)*, *Section 8.3: Hall sensor feedback processing*, and *Section 8.4: Encoder sensor feedback processing* for further details.

The selection of speed/position feedback can be performed through correct settings in the .h parameter files (generated by the ST MC Workbench GUI) used to initialize the MC Application during its boot stage.

8.1 Sensorless algorithm (BEMF reconstruction)

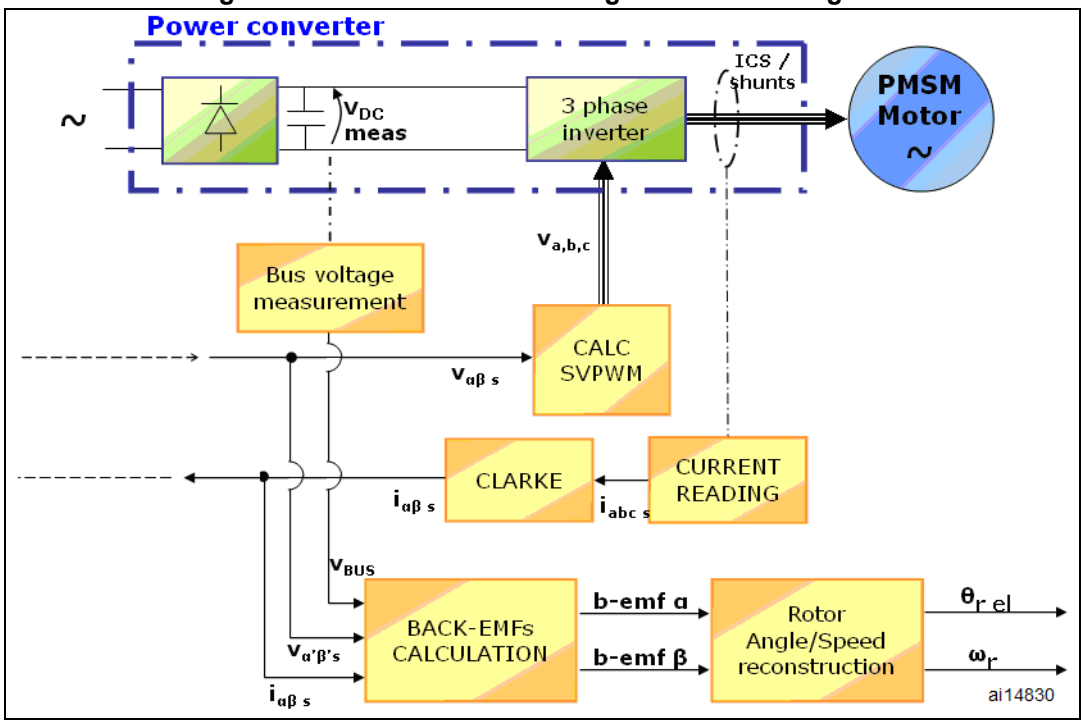
This firmware library provides a complete solution for sensorless detection of rotor position/speed feedback, which is based on the state observer theory. The implemented algorithm is applicable to both SM-PM and IPM synchronous motors, as explained in [5] (*Section A.1: References*). A theoretical and experimental comparison between the implemented rotor flux observer and a classical VI estimator [6](Appendix *Section A.1: References*) has pointed out the observer's advantage, which turns out to be a clearly reduced dependence on the stator resistance variation and an overall robustness in terms of parameter variations.

A state observer, in control theory, is a system that provides an estimation of the internal state of a real system, given its input and output measurement.

In our case, the internal states of the motor are the back-emfs and the phase currents, while the input and output quantities supplied are the phase voltages and measured currents, respectively (see *Figure 17*).

DC bus voltage measurement is used to convert voltage commands into voltage applied to motor phases.

Figure 63. General sensorless algorithm block diagram



The observed states are compared for consistency with the real system via the phase currents, and the result is used to adjust the model through a gain vector (K1, K2).

The motor back-emfs are defined as:

$$e_\alpha = \Phi_m p\omega_t \cos(p\omega_t t)$$
$$e_\beta = -\Phi_m p\omega_t \sin(p\omega_t t)$$

As can be seen, they hold information about the rotor angle. Then, back-emfs are fed to a block which is able to reconstruct the rotor electrical angle and speed. This latter block can be a PLL (Phase-Locked Loop) or a CORDIC (COordinate Rotation DIgital Computer), depending on the user's choice.

In addition, the module processes the output data and, by doing so, implements a safety feature that detects locked-rotor condition or malfunctioning.

Figure 64 shows a scope capture taken while the motor is running in field-oriented control (positive rolling direction). The yellow and the red waveforms (C1,C2) are respectively the observed back-emfs alpha and beta. The blue square wave (C3) is a signal coming from a Hall sensor cell placed on the a-axis. The green sinewave is current i_a (C4).

In confidential distribution, the classes that implement the sensorless algorithm are provided as compiled object files. The source code is available free of charge from ST on request. Please contact your nearest ST sales office.

8.1.1 A priori determination of state observer gains

The computation of the initial values of gains K1 and K2 is based on the placement of the state observer eigenvalues. The required motor parameters are r_s (motor winding resistance), L_s (motor winding inductance), T (sampling time of the sensorless algorithm, which coincides with FOC and stator currents sampling).

The motor model eigenvalues could be calculated as:

$$e_1 = 1 - \frac{r_s T}{L_s}$$

$$e_2 = 1$$

The observer eigenvalues are placed with:

$$e_{1obs} = \frac{e_1}{f}$$

$$e_{2obs} = \frac{e_2}{f}$$

Typically, as a rule of the thumb, set $f = 4$;

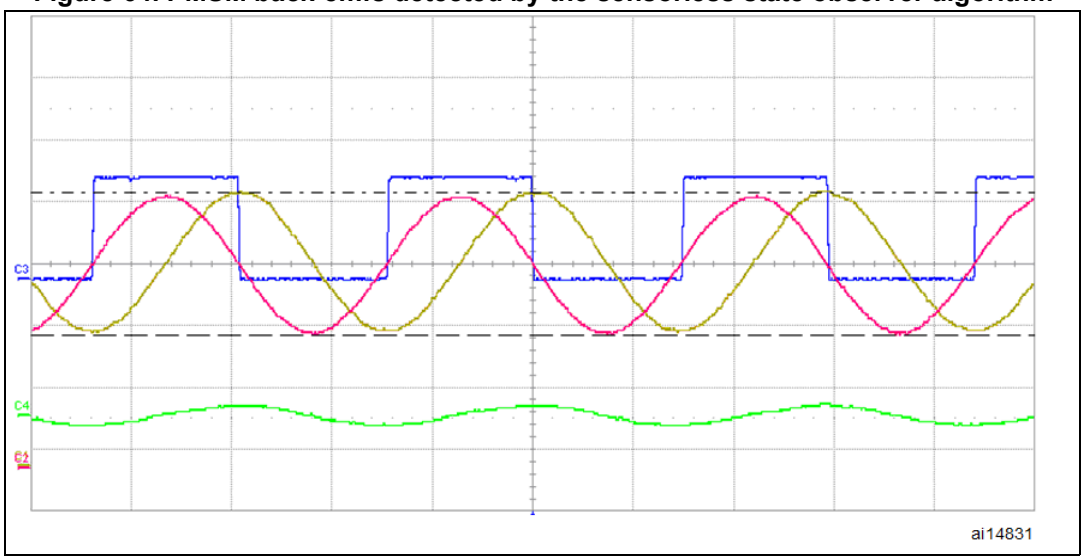
The initial values of K1 and K2 could be calculated as:

$$K_1 = \frac{e_{1obs} + e_{2obs} - 2}{T} + \frac{r_s}{L_s}$$

$$K_2 = \frac{L_s(1 - e_{1obs} - e_{2obs} + e_{1obs}e_{2obs})}{T^2}$$

This procedure is followed by the ST MC Workbench GUI to calculate proper state observer gains. It is also possible to modify these values using other criteria or after fine-tuning.

Figure 64. PMSM back-emfs detected by the sensorless state observer algorithm



1. C1= b-emf alpha
2. C2 = b-emf beta
3. C3 = Hall 1
4. C4 = phase A, measured current

More information on how to fine-tune parameters to make the firmware suit the motor can be found in *Section 11: Full LCD user interface*.

8.2 Sensorless algorithm: High frequency injection(HFI)

Overview

A new sensorless algorithm (ST patent pending) is available for I-PMSM motors that, by exploiting the peculiar anisotropy of their magnetic structure, are able to detect rotor angular position at very low speeds and at standstill.

The algorithm is based on injection of a small high frequency voltage signal along a given direction so that, thanks to the rotor saliency, a periodic current signal is generated whose amplitude is function of the phase displacement between rotor position and injection angle.

Consequently, a robust rotor position tracking, unaffected by parameter variations (speed and load), is obtained by minimizing the amplitude of the above mentioned signal response.

This new high frequency injection algorithm can work in synergy with the back-emfs observer (section 8.1) in order to cover, complementarily, a broad speed operating range: zero and very low speed the first, low and up to deep flux weakening the second.

The HFI can be enabled on STM32F30x and STM32F4x, taking full advantage of their floating point unit (VFP).

Incremental system build

The tuning of an HFI-based system can be accomplished by means of an “incremental system build” path, whose steps involve the following strict steps: utilization of the STMCWB as configurator, a toolchain for code building and flashing, trials on the system (taking advantage of the DAC tracer and STMCWB serial communication), and then back to STMCWB to set the parameters that have been found.

In particular, the defined path goes through:

0. Complete an hardware/firmware setup and related STMCWB configuration that is able to run the motor in FOC sensorless, observer + PLL mode, in a speed range from 10% to nominal;
1. STMCWB configurator:
   a) enable “Sensorless HFI + Observer” as speed sensor;
   b) set an HFI “Amplitude” which, considering the (default) HFI frequency and motor RL figure allows the flow of – roughly, as starting value – 5% of the motor nominal current;
   c) enable HFI Debug mode;
   d) leave other HFI parameters as default;
   e) enable DAC functionality, and set “HFI current” and “Ia” as CH1 and CH2 variables (related of course to the motor drive under testing, between M1 and M2);
   f) generate h files
2. toolchain: build and download; this step, actually, follows any new settings in the STMCWB configuration, before it can be re-tested;
3. system testing, applicability of HFI to the motor:
   a) arrange the necessary hardware, oscilloscope triggering and probes to capture DAC tracers, power source;
   b) run the motor giving a “start motor command” (from LCD UI or STMCWB serial)
      – the motor will not move at all because, at step 1.c, debug mode has been activated
      – after the oscilloscope has captured the waveforms, it’s possible to move back the state machine giving a “Stop Motor” command (by LCD or serial UI, for instance);
   c) analyze the oscilloscope capture:
      – if “HFI current” (CH1) has a periodic waveform and its period is half that of “Ia” (CH2), similarly to what shown in Figure 1, then the IPMSM motor under testing is suitable for this ST HFI sensorless algorithm, it’s possible to proceed with step 4)
      – if CH1 is clearly periodic but its period is wrong, then the motor it’s not suitable for HFI algorithm;
      – if CH1 is flat or not well defined periodicity , restart from step 1)b, increase (incrementally, up to a viable value) the HFI “Amplitude” . At that point, if CH1 acquires the right shape then the motor is suitable for HFI, it’s possible to proceed with step 4)
4. System testing, initial angle detection:
   a) modify the DAC variable CH2 (for instance using LCD UI or STMCWB serial) by setting “HFI initial angle PLL”, run the motor (as described in 3)b);
   b) analyze the oscilloscope capture:
      – if CH2 converges asymptotically to a value, which depends from rotor angle, before the allowed time is ended (which is evident from CH2 itself), as

shown in Figure 2, then “Initial angle PLL” gains are ok, it’s possible to proceed with step 4)c

– if CH2 oscillates around a value, which depends from rotor angle, then decrease “Init angle PLL” KI or increase KP, build, flash and try again;

– if the trend of CH2 is clearly interrupted before reaching its asymptotical value, then increase KI or increase Scan Rotation number (the procedure will take more time, in this case), build, flash and try again;

c) Read the variable “HFI saturation difference” from STMCWB serial registers

– If the variable is around 5-10% of the nominal current, then it can be copied in the STMCBW configurator as “Min saturation Difference”; it’s possible to proceed with step 5)

– If the variable is lower than 5% of the nominal current, then increase (incrementally, up to a viable value) in the STMCWB configurator the parameter “Amplitude boost”; build, flash, and try again;

5. System testing, angle tracking:

a) Run the motor, as described in 3)b, analyze the oscilloscope capture: in particular, variable CH2 has to show the pattern of Figure 2, stage 3:

– if CH2 converges asymptotically to a value, which depends from rotor angle, before the allowed time is ended then HFI PI gains are ok; it’s possible to proceed with step 5)b

– if CH2 oscillates around a value, which depends from rotor angle, then decrease HFI KI or increase KP, build, flash and try again;

– if the trend of CH2 is clearly interrupted before reaching its asymptotical value, then increase KI, build, flash and try again;

b) If possible, turn the rotor by hand or other means, otherwise skip to step 6):

– if CH2 should show the HFI’s measured rotor angle, it’s possible to proceed with step 6);

6. System testing, run mode:

a) Disable “HFI debug mode” from STMCWB;

b) Set an “HFI-STO threshold” in the range of 20% of the nominal speed;

c) build the workspace, and download;

d) Set an initial target speed (from STMCWB serial, LCD UI or other UI) lower than what configured in as “HFI-STO threshold”, say 5% of the nominal speed, so as that HFI only is used for this testing;

e) Run the motor! If it’s ok, it’s possible now to configure the transition between HFI and STO, and vice versa. This usually happens at about 10% of the motor nominal speed; please refer to STMCWB documentation for related parameters.

Figure 65. IPMSM anisotropy fitting HFI algorithm

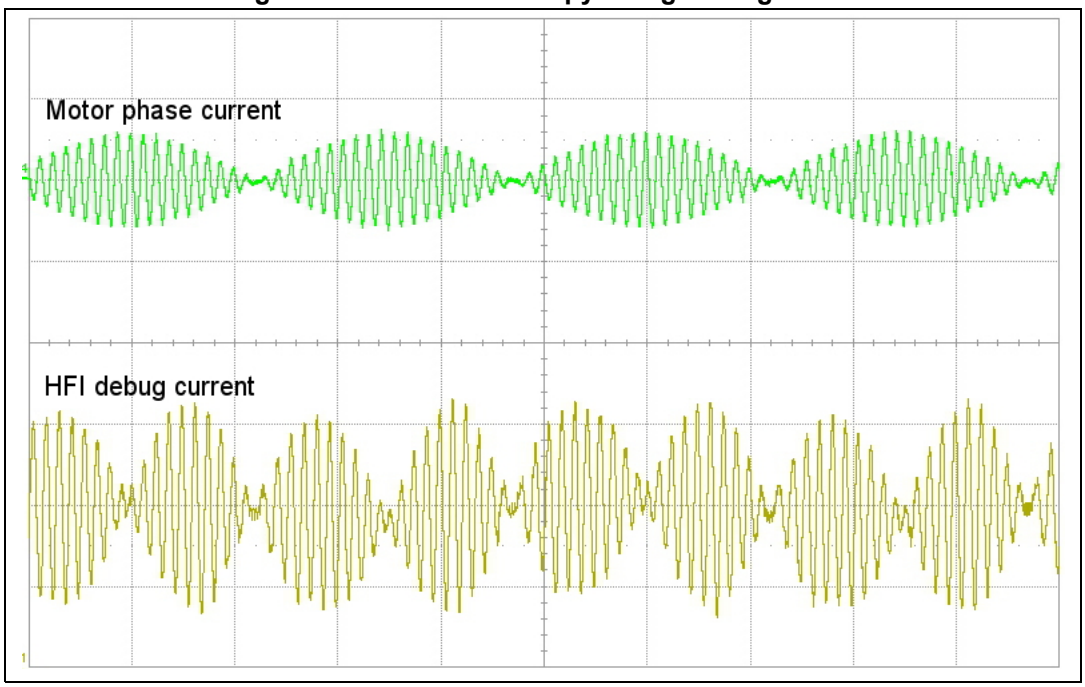
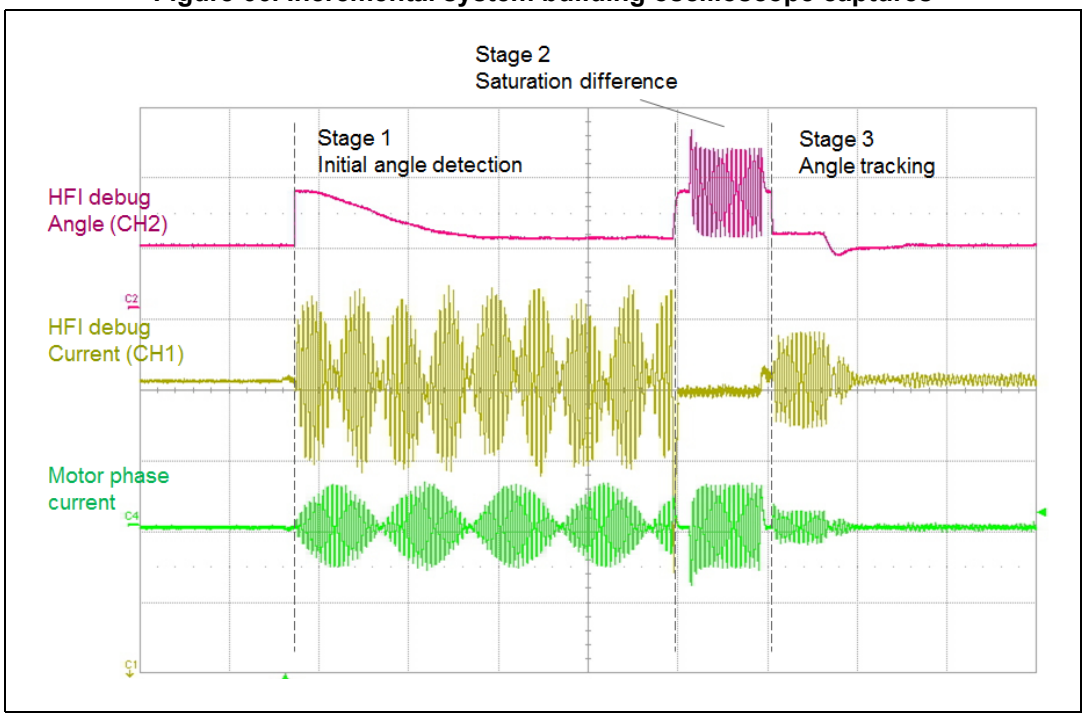


Figure 66. Incremental system building oscilloscope captures



8.3 Hall sensor feedback processing

8.3.1 Speed measurement implementation

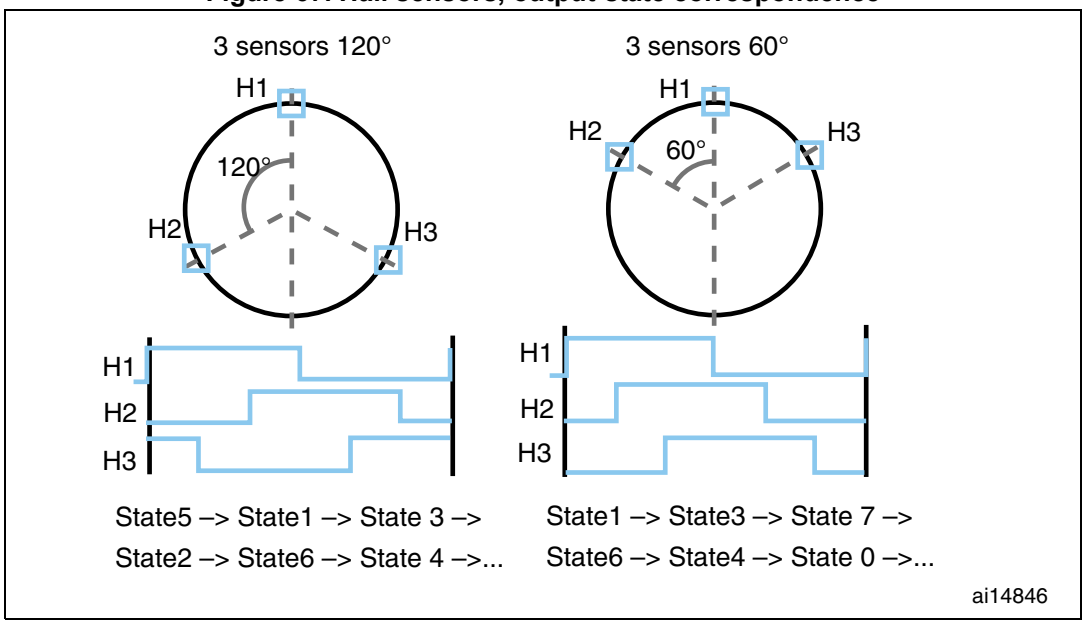
Thanks to the STM32 general-purpose timer (TIMx) features, it is very simple to interface the microcontroller with three Hall sensors. When the TI1S bit in the TIMx_CR2 register is set, the three signals on the TIMx_CH1, TIMx_CH2 and TIMx_CH3 pins are XORed and the resulting signal is connected to the TIMx input capture.

Thus, the speed measurement is converted into the period measurement of a square wave with a frequency six times higher than the real electrical frequency. The only exception is that the rolling direction, which is not extractable from the XORed signal, is performed by a direct access to the three Hall sensor outputs.

Rolling direction identification

As shown in *Figure 67*, it is possible to associate any of Hall sensor output combinations with a state whose number is obtainable by considering H3-H2-H1 as a three-digit binary number (H3 is the most significant bit).

Figure 67. Hall sensors, output-state correspondence



Consequently, it is possible to reconstruct the rolling direction of the rotor by comparing the present state with the previous one. In the presence of a positive speed, the sequence must be as illustrated in *Figure 67*.

Period measurement

Although the principle for measuring a period with a timer is quite simple, it is important to keep the best resolution, in particular for signals, such as the one under consideration, that can vary with a ratio easily reaching 1:1000.

In order to always have the best resolution, the timer clock prescaler is constantly adjusted in the current implementation.

The basic principle is to speed up the timer if the captured values are too low (for an example of short periods, see *Figure 68*), and to slow it down when the timer overflows between two consecutive captures (see the example of large periods in *Figure 69*).

Figure 68. Hall sensor timer interface prescaler decrease

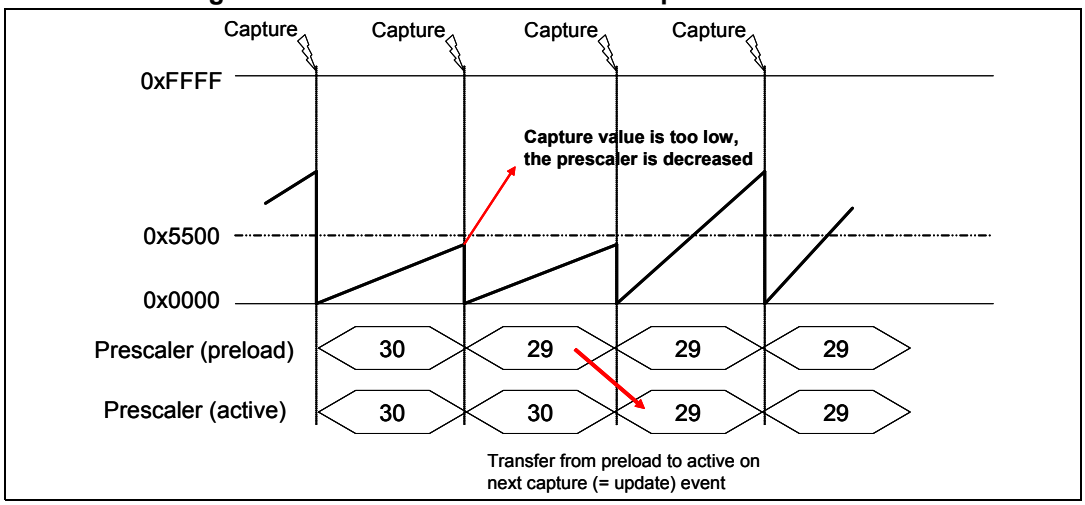
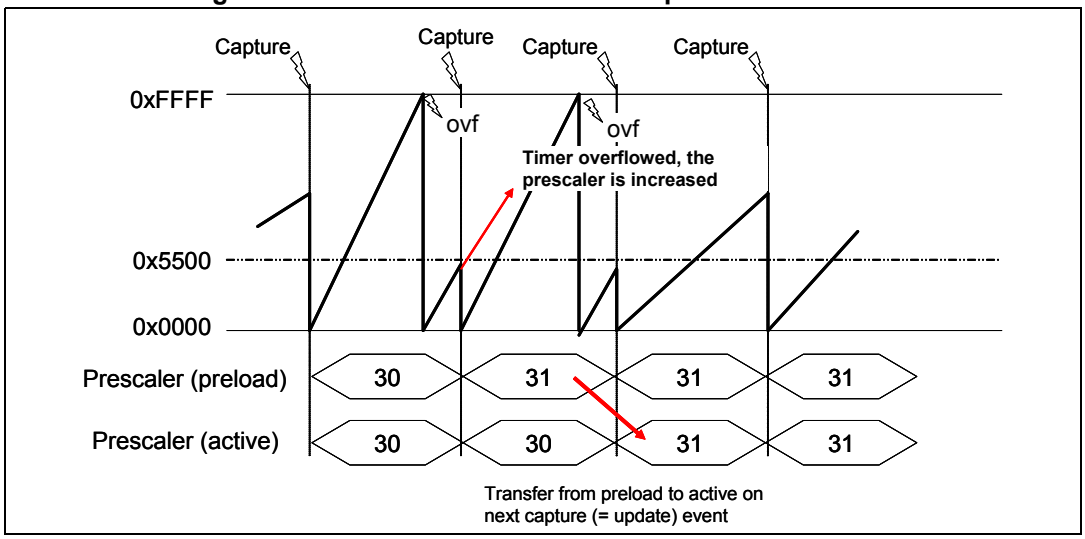


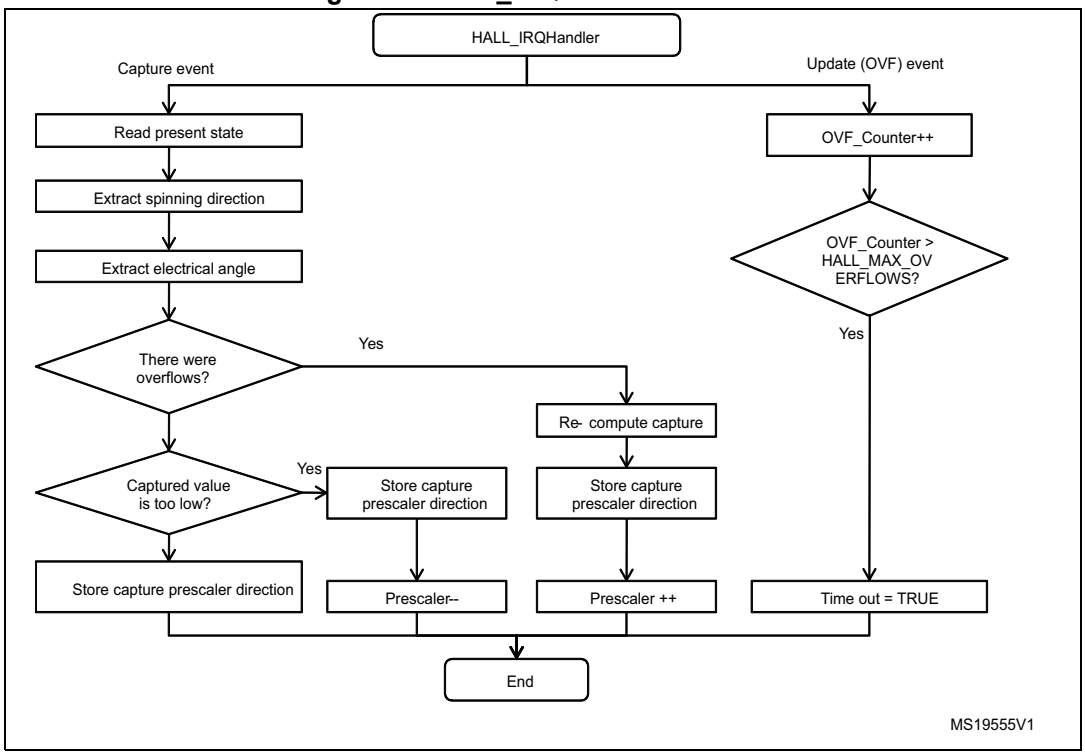
Figure 69. Hall sensor timer interface prescaler increase



The prescaler modification is done in the capture interrupt, taking advantage of the buffered registers: the new prescaler value is taken into account only on the next capture event, by the hardware, without disturbing the measurement.

Further details are provided in the flowchart shown in *Figure 70*, which summarizes the actions taken into the TIMx_IRQHandler.

Figure 70. TIMx_IRQHandler flowchart



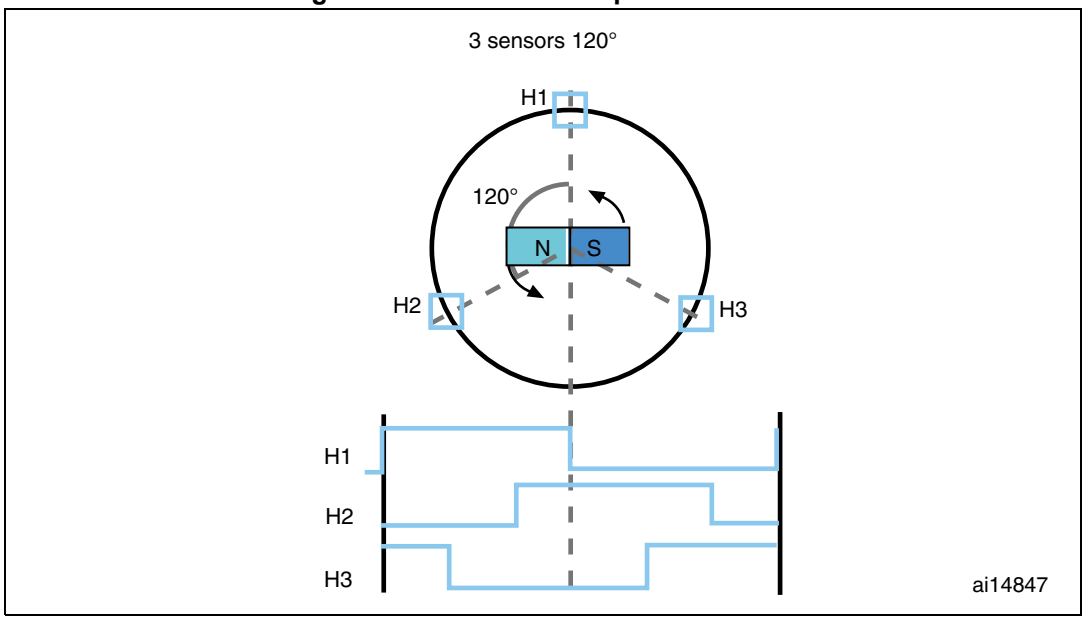
8.3.2 Electrical angle extrapolation implementation

As shown in *Figure 70*, the speed measurement is not the only task performed in TIMx_IRQHandler. As well as the speed measurement, the high-to-low or low-to-high transition of the XORed signal also gives the possibility of synchronizing the software variable that contains the present electrical angle.

The synchronization is performed avoiding abrupt changes in the measured electrical angles. In order to do this, the difference between the expected electrical angle, computed from the last speed measurement, and the real electrical angle, coming from the Hall sensor signals (see *Figure 95*) is computed. The new speed measurement is adjusted with this information in order to compensate for the difference.

As can be seen in *Figure 71*, any Hall sensor transition gives very precise information about the rotor position.

Figure 71. Hall sensor output transitions



Furthermore, the utilisation of the FOC algorithm implies the need for a good and constant rotor position accuracy, including between two consecutive falling edges of the XORed signal (which occurs each 60 electrical degrees). For this reason, it is clearly necessary to interpolate rotor electrical angle information. For this purpose, the latest available speed measurement (see *Section 10.4: Measurement units*) in dpp format (adjusted as described above) is added to the present electrical angle software variable value, any time the FOC algorithm is executed. See *Section 10.4: Measurement units*.

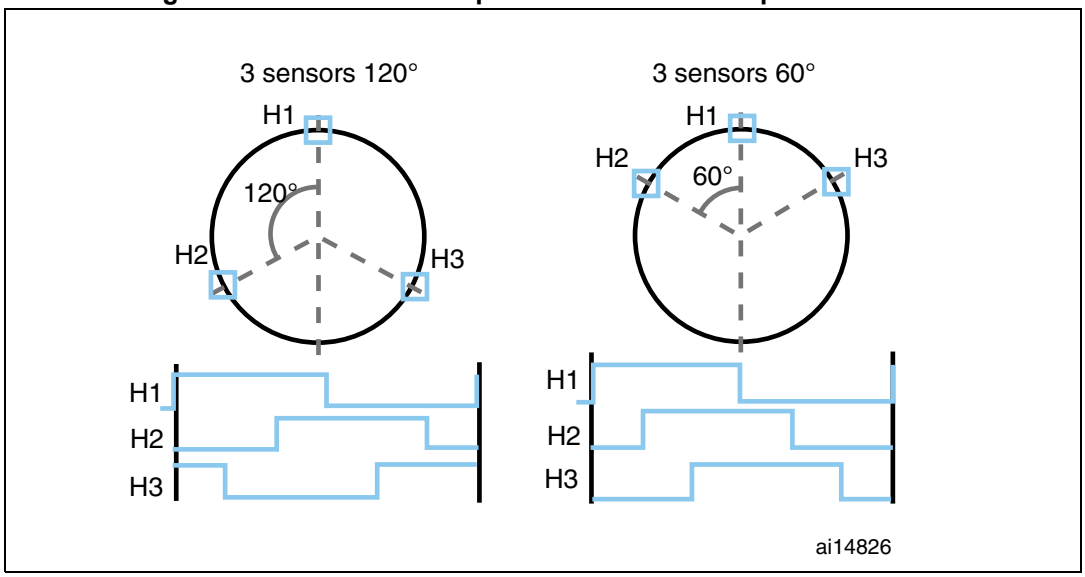
8.3.3 Setting up the system when using Hall-effect sensors

Hall-effect sensors are devices capable of sensing the polarity of the rotor's magnetic field. They provide a logic output, which is 0 or 1 depending on the magnetic pole they face and thus, on the rotor position.

Typically, in a three-phase PM motor, three Hall-effect sensors are used to feed back the rotor position information. They are usually mechanically displaced by either 120° or 60° and the presented firmware library was designed to support both possibilities.

As shown in *Figure 72*, the typical waveforms can be visualized at the sensor outputs in case of 60° and 120° displaced Hall sensors. More particularly, *Figure 72* refers to an electrical period (that is, one mechanical revolution, in case of one pole pair motor).

Figure 72. 60° and 120° displaced Hall sensor output waveforms



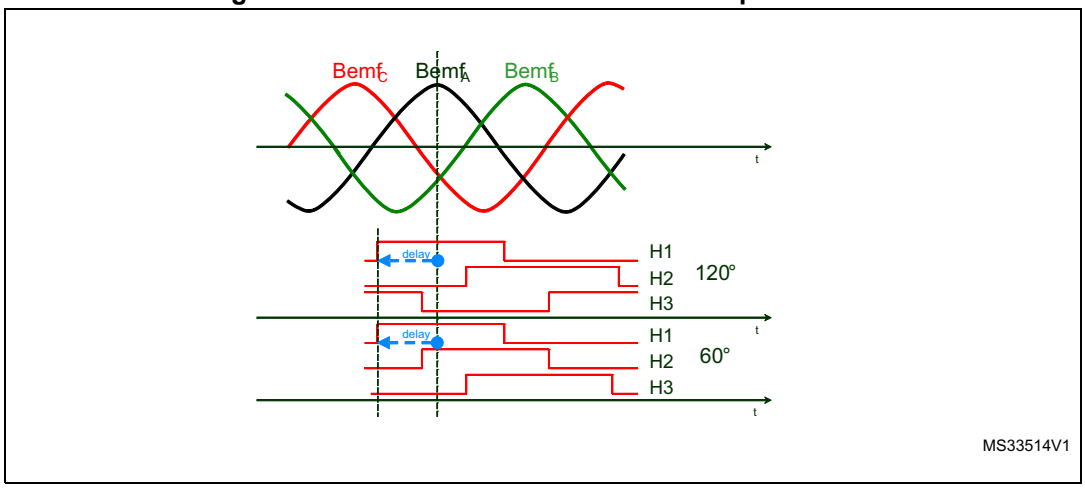
Because the rotor position information they provide is absolute, there is no need for any initial rotor prepositioning. Particular attention must be paid, however, when connecting the sensors to the proper microcontroller inputs.

This software library assumes that the positive rolling direction is the rolling direction of a machine that is fed with a three-phase system of positive sequence. In this case, to work correctly, the software library expects the Hall sensor signal transitions to be in the sequence shown in *Figure 72* for both 60° and 120° displaced Hall sensors.

For these reasons, it is suggested to follow the instructions given below when connecting a Hall-sensor equipped PM motor to your board:

1. Turn the rotor by hand in the direction assumed to be positive and look at the B-emf induced on the three motor phases. If the real neutral point is not available, it can be reconstructed by means of three resistors, for instance.
2. Connect the motor phases to the hardware respecting the positive sequence. Let “phase A”, “phase B” and “phase C” be the motor phases driven by TIM1_CH1, TIM1_CH2 and TIM1_CH3, respectively (for example, when using the MB459 board, a positive sequence of the motor phases could be connected to J5 2,1 and 3).
3. Turn the rotor by hand in the direction assumed to be positive, look at the three Hall sensor outputs (H1, H2 and H3) and connect them to the selected timer on channels 1, 2 and 3, respectively, making sure that the sequence shown in *Figure 72* is respected.
4. Measure the delay in electrical degrees between the maximum of the B-emf induced on phase A and the first rising edge of signal H1.
5. Enter two parameters displacement and delay found in the ST MC Workbench GUI, inside the windowrelated to motor speed and position sensor. An example with delay equal to 270° is illustrated in *Figure 73*.

Figure 73. Determination of Hall electrical phase shift



8.4 Encoder sensor feedback processing

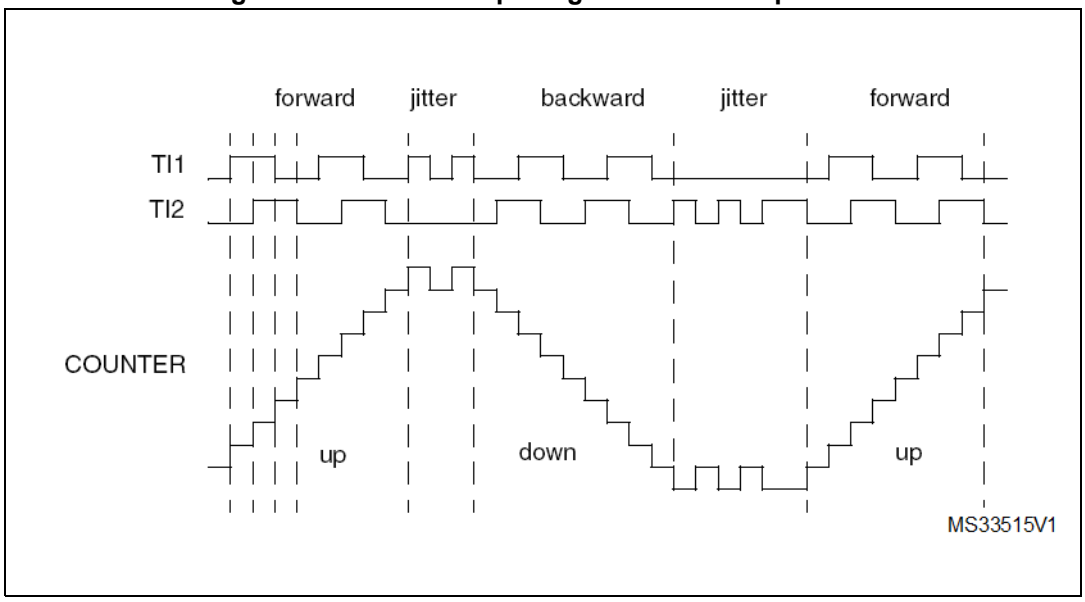
Quadrature incremental encoders are widely used to read the rotor position of electric machines.

As the name implies, incremental encoders actually read angular displacements with respect to an initial position: if that position is known, then the rotor absolute angle is known too. For this reason, it is always necessary, when processing the encoder feedback, to perform a rotor prepositioning before the first startup after any fault event or microcontroller reset.

Quadrature encoders have two output signals (represented in *Figure 74* as TI1 and TI2). Together with the Root part number 1 standard timer in the encoder interface mode, once the said alignment procedure has been executed, it is possible to get information about the actual rotor angle - and therefore the rolling direction - by simply reading the counter of the timer used to decode encoder signals.

For the purpose of MC Library and as information provided by the MC API, the rotor angle is expressed in ‘s16degrees’ (see *Section 10.4: Measurement units*).

Figure 74. Encoder output signals: counter operation



The rotor angular velocity can be easily calculated as a time derivative of the angular position.

8.4.1 Setting up the system when using an encoder

Extra care should be taken over what is considered to be the positive rolling direction: this software library assumes that the positive rolling direction is the rolling direction of a machine that is fed with a three-phase system of positive sequence.

Because of this, and because of how the encoder output signals are wired to the microcontroller input pins, it is possible to have a sign discrepancy between the real rolling direction and the direction that is read. To avoid this kind of reading error, apply the following procedure:

1. Turn the rotor by hand in the direction assumed to be positive and look at the B-emf induced on the three motor phases. A neutral point may need to be reconstructed with three resistors if the real one is not available.
2. Connect the motor phases to the hardware respecting the positive sequence (for instance when using the MB459 board, a positive sequence of the motor phases may be connected to J5 2,1 and 3).
3. Run the firmware in the encoder configuration and turn by hand the rotor in the direction assumed to be positive. If the measured speed shown on the LCD is positive, the connection is correct; otherwise, it can be corrected by simply swapping and rewiring the encoder output signals.

   If this is not practical, a software setting may be modified instead, using the ST MC Workbench GUI (see the GUI help file).

Alignment settings

The quadrature encoder is a relative position sensor. Considering that absolute information is required for performing field-oriented control, it is necessary to establish a 0° position. This task is performed by means of an alignment phase (*Section 11.2.3: Configuration and debug page*, callout 9 in *Figure 93: Configuration and debug page*), and shall be carried out

at the first motor startup and optionally after any fault event. It consists of imposing a stator flux with a linearly increasing magnitude and a constant orientation.

If properly configured, at the end of this phase, the rotor is locked in a well-known position and the encoder timer counter is initialized accordingly.

9 Working environment

The working environment for the Motor Control SDK is composed of:

- A PC
- A third-party integrated development environment (IDE)
- A third-party C-compiler
- A JTAG/SWD interface for debugging and programming
- An application board with an STM32F0x, STM32F100xx/STM32F103xx, STM32F2xx, STM32F30x or STM32F4xx properly designed to drive its power stage (PWM outputs to gate driver, ADC channels to read currents, DC bus voltage). Many evaluation boards are available from ST, some of them have an ST-link programmer on board.
- A three-phase PMSM motor

Table 12 explains the MC SDK file structure for both Web and confidential distributions.

Table 12. File structure

File	Subfile	Description
MClibrary		Source file of the MC library layer
	interface	Public definitions (interfaces) of classes
	inc (available only in confidential distribution)	Private definitions (data structure) of classes
	src (available only in confidential distribution)	Source files
	common	Public definitions (interfaces) of classes and definitions exported up to the highest level (PI, Digital Output, reference frame transformation)
	obj	Compiled classes
MCApplication		Source file of the MC application layer
	interface	Public definitions (interfaces) of classes
	inc	Private definitions (data structure) of classes
	src	Source files
UILibrary		Source file of the User Interface layer
	interface	Public definitions (interfaces) of classes
	inc	Private definitions (data structure) of classes
	src	Source files
	STMFC	LCD graphics library
Libraries		
	FreeRTOS source	FreeRTOS V1.6 distribution (GNU GPL license, http://freertos.org/a00114.html)
	CMSIS	Cortex™ Microcontroller Software Interface Standard v1.30

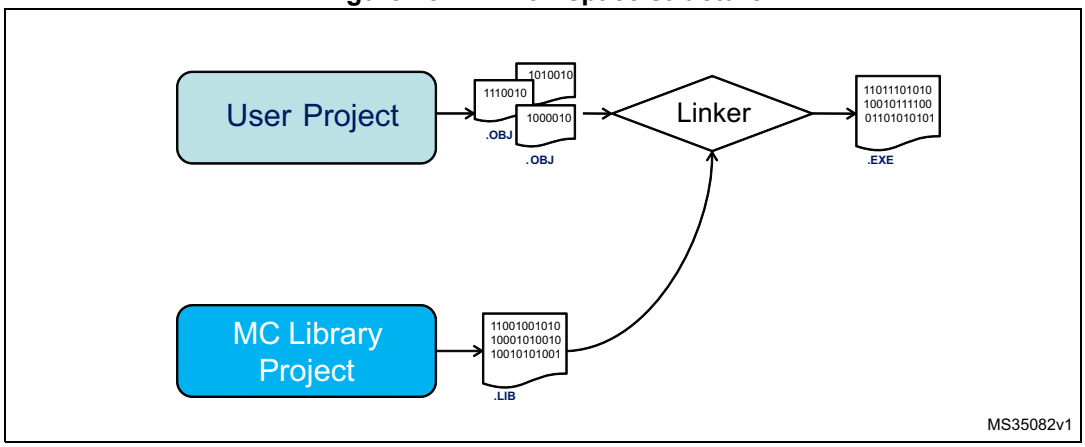
Table 12. File structure (continued)

File	Subfile	Description
	STMF0xx_StdPeriph_Driver	STMF0xx Standard Peripherals Library Drivers V1.0.0
	STMF10x_StdPeriph_Driver	STMF10x Standard Peripherals Library Drivers V3.5.0
	STMF2xx_StdPeriph_Driver	STMF2xx Standard Peripherals Library Drivers V1.0.0
	STMF30x_StdPeriph_Driver	STMF30x Standard Peripherals Library Drivers V1.0.1
	STMF4xx_StdPeriph_Driver	STMF4xx Standard Peripherals Library Drivers V1.0.0
SystemDriveParams		Contains default parameter files (unpacked at installation time, referring to the STM32 MC Kit) or those generated by the ST MC workbench GUI according to user's system
Utilities	STM32_EVAL	Contains code needed for specific functions of ST evaluation boards (LCD drivers, I/O pin assignment, port expanders).
	WB_Projects	Contains the ST MC Workbench project ready to startup a new design using one of the available STM32 EVAL boards compatible with STM32 FOC lib.
Project		Contains source files of the demonstration user layer application and configuration files for IDEs. In addition, inside each IDE folder (in \MC library Compiled\exe), compiled MC library is provided (in case of web distribution) or created/modified by the IDE (in case of confidential distribution) for single and dual motor drive.
FreeRTOSProject		Contains source files of the demonstration user layer application based on FreeRTOS and configuration files for IDEs. In addition, inside each IDE folder (in \MC library Compiled\exe), compiled MC library is provided (in case of web distribution) or created/modified by the IDE (in case of confidential distribution) for single and dual motor drive.
LCDProject		Contains source files of the optional LCD user interface and configuration files for IDEs
	HEX	Contains the compiled version of LCD firmware ready to be flashed using ST Link utility

9.1 Motor control workspace

The Motor Control SDK is composed of two projects (as shown in *Figure 75*), which constitute the MC workspace.

Figure 75. MC workspace structure



The Motor Control Library project: the collection of all the classes developed to implement all the features. Each class has its own public interface. A public interface is the list of the parameters needed to identify an 'object' of that kind and of the methods (or functions) available. Note that, in the case of a derivative class, applicable methods are those of the specific derived plus those of the base class. Further detail is provided in the *Advanced developers guide for STM32F0x/F100xx/F103xx/ STM32F2xx/F30x/F4xx MCUs PMSM single/dual FOC library* (UM1053).

All these interfaces constitute the Motor Control Library Interface. The Motor Control Library project is independent from system parameters (the only exception is single/dual drive configuration), and is built as a compiled library, not as an executable file (see *Section 9.3*).

The user project: it contains both the MC Application layer and the demonstration program that makes use of that layer through its MC API and provides the required clockings and access to Interrupt Handlers. Parameters and configurations related to user's application are used here to create right objects in what is called the run-time system 'boot'. The Motor Control API is the set of commands granted to the upper layer. The program can run some useful functions (depending on user options), such as serial communication, LCD/keys interface, system variables displaying through DAC.

13 user project workspaces are available. They differ in the supported STM32 family, IDE supported, how they generate the clocks: a simple time base itself or an Operating System

(FreeRTOS). The first 8 are for IAR EWARM IDE and are stored in the folder Project\EWARM:

- STM32F0xx_Workspace for STM32F0xx devices and simple time base
- STM32F10x_Workspace for both STM32F100xx and STM32F103xx devices and simple time base
- STM32F10x_Example for both STM32F100xx and STM32F103xx devices with simple time base and ready-to-use examples.
- STM32F2xx_Workspace for STM32F2xx devices and simple time base
- STM32F4xx_Workspace for STM32F4xx devices and simple time base
- STM32F10x_RTOS_Workspace for both STM32F100xx and STM32F103xx devices and FreeRTOS
- STM32F2xx_RTOS_Workspace for STM32F2xx devices and FreeRTOS
- STM32F30x_Workspace for STM32F302/303 devices and simple time base.

The remaining 5 are for Keil uVision and are stored in the folder Project\MDK-ARM:

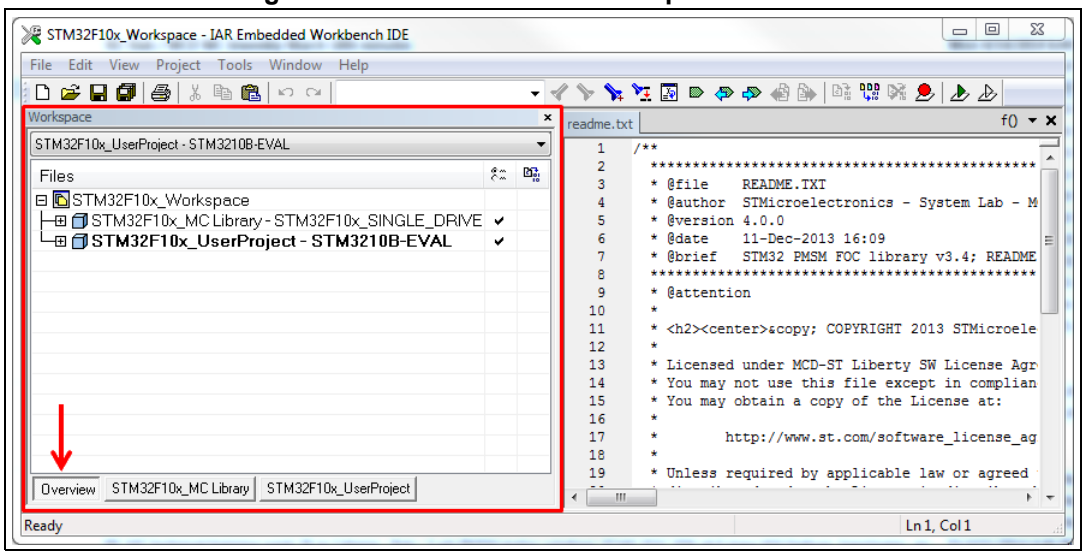
- STM32F0xx_Workspace for STM32F0xx devices and simple time base
- STM32F10x_Workspace for both STM32F100xx and STM32F103xx devices and simple time base
- STM32F2xx_Workspace for STM32F2xx devices and simple time base
- STM32F4xx_Workspace for STM32F4xx devices and simple time base
- STM32F30x_Workspace for STM32F302/303 devices and simple time base.

See *Section 10.3: How to create a user project that interacts with the MC API* to understand how to create a brand new user project.

In *Section 9.4: User project*, built .lib files are linked with the user project in order to generate the file that can be downloaded into the microcontroller memory for execution.

Figure 76 provides an overview of the IAR EWARM IDE workspace (located in the Installation folder `\Project\EWARM\STM32F10x_Workspace.eww`). The following sections provide details on this. The equivalent workspace based on FreeRTOS is located in the Installation folder `\FreeRTOSProject\EWARM\STM32F10x_RTOS_Workspace.eww`.

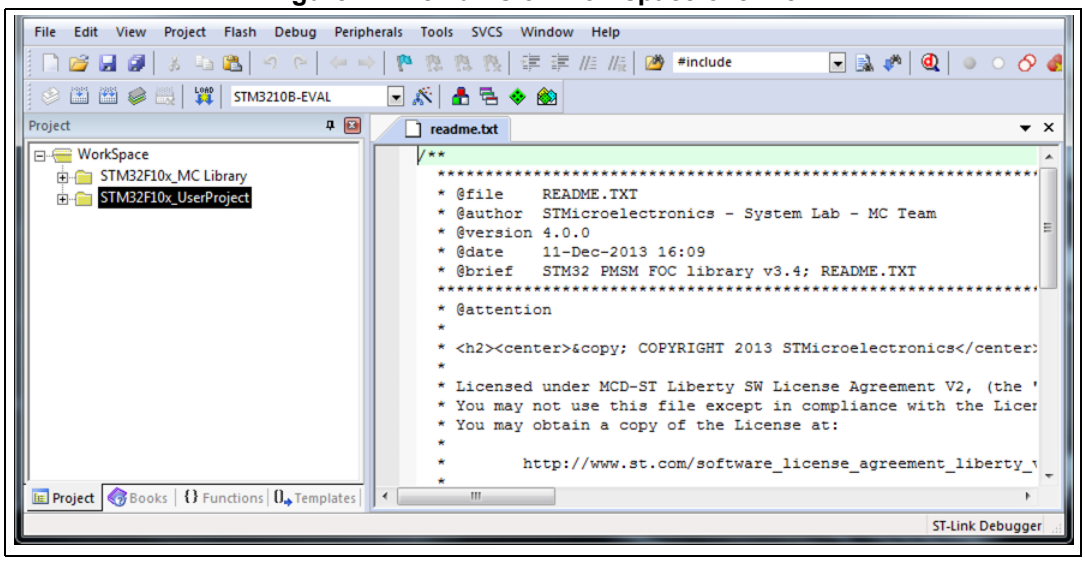
Figure 76. IAR EWARM IDE workspace overview



Section 9.2: MC SDK customization process provides the procedure for customizing the Motor Control SDK.

Figure 77 provides an overview of the Keil uVision workspace (located in the Installation folder \Project\MDK-ARM\STM32F10x_Workspace.uvmpw).

Figure 77. Keil uVision workspace overview

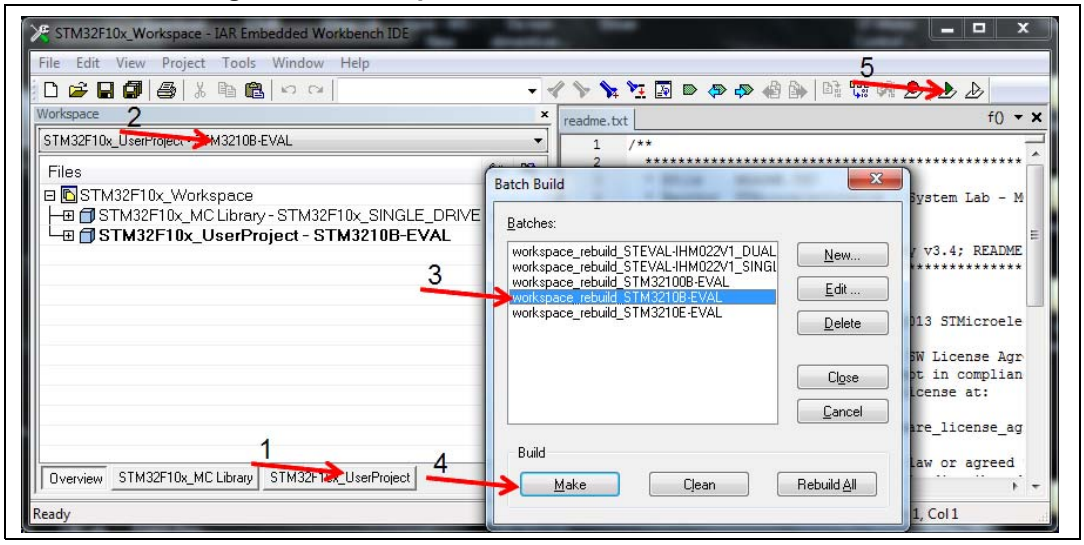


9.2 MC SDK customization process

This section explains how to customize the Motor Control SDK using IAR EWARM IDE, or Keil uVision, so that it corresponds to the user's current system.

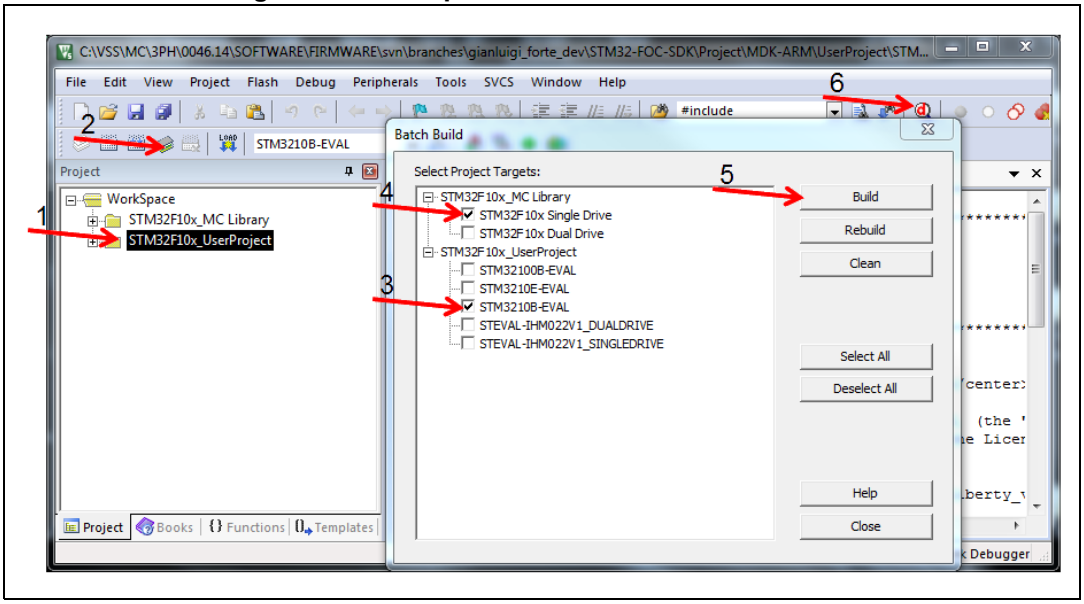
1. Using the ST MC Workbench GUI configure the firmware according to the HW, motor and specific drive setting of the system. This part of the process ends by generating the .h parameters in the correct directory (`Installation folder\SystemDriveParams`).
2. If the system is configured to enable the full LCD User Interface, download the specific firmware. See *Section 9.5: Full LCD UI project*.
3. Using Keil uVision follow the point 7, 8, 9, 10. Open one of the MC workspaces:
   - FreeRTOS based:
     Installation folder\FreeRTOSProject\EWARM\STM32F10x_RTOS_Workspace.eww
     Installation folder\FreeRTOSProject\EWARM\STM32F2xx_RTOS_Workspace.eww
   - Non-FreeRTOS:
     Installation folder\Project\EWARM\STM32F0xx_Workspace.eww
     Installation folder\Project\EWARM\STM32F10x_Workspace.eww
     Installation folder\Project\EWARM\STM32F2xx_Workspace.eww
     Installation folder\Project\EWARM\STM32F3xx_Workspace.eww
     Installation folder\Project\EWARM\STM32F4xx_Workspace.eww
4. Enable the user project (callout 1 in *Figure 78*) and select the appropriate option from the combo-box (callout 2 in *Figure 78*). If none of the boards displayed is in use, read *Section 9.4: User project* to perform a correct configuration.
5. Press F8 to batch-build the entire workspace. The dialog box shown in *Figure 78: Workspace batch build for IAR EWARM IDE* appears.
6. Select a batch command (callout 3, *Figure 78*) as for step 4, then click the Make button to make the build (callout 4, *Figure 78*). If no error or relevant warning appears, download the firmware (callout 5, *Figure 78*) and do a test run.

Figure 78. Workspace batch build for IAR EWARM IDE



7. Open one of the MC workspaces:
   Installation folder\Project\MDK-ARM\STM32F0xx_Workspace.uvmpw
   Installation folder\Project\MDK-ARM\STM32F10x_Workspace.uvmpw
   Installation folder\Project\MDK-ARM\STM32F2xx_Workspace.uvmpw
   Installation folder\Project\MDK-ARM\STM32F3xx_Workspace.uvmpw
   Installation folder\Project\MDK-ARM\STM32F4xx_Workspace.uvmpw
8. Enable the UserProject (callout 1 in *Figure 79*) right click on it and select "Set as Active Project" according the evaluation board used. If none of the boards displayed is in use, read Section 9.5: User project to perform a correct configuration.
9. Press batch build button (callout 2 in *Figure 79*) The dialog box shown in *Figure 79*: Batch Build appears.
10. Select the configuration to be build according the step 7 (callout 3 in *Figure 79*) and selecting the proper conflagration of the MC Library (Single or Dual drive) (callout 4 in *Figure 79*). Then click Build button to make the build (callout 5 in *Figure 79*). If no error or relevant warning appears, download the firmware (callout 6, *Figure 79*) and do a test run.

Figure 79. Workspace batch build for Keil uVision



Note: When the system configuration or parameters are modified, just the User project requires to be recompiled. The batch build procedure is requested just if the MC Library is provided as source code and only for the first compilation for both single and dual drive configuration.

9.3 Motor control library project (confidential distribution)

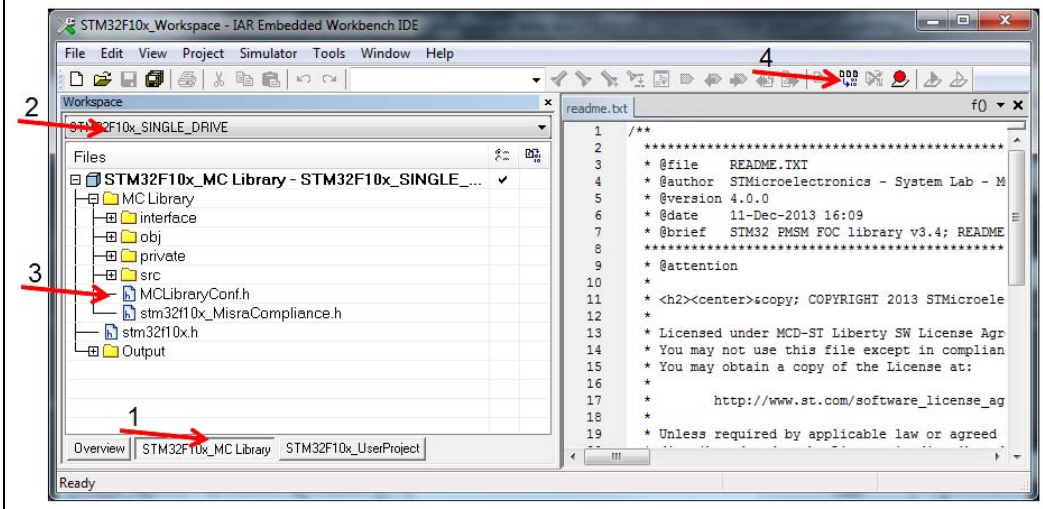
The MC Library project (available only in confidential distribution) is a collection of classes related to motor control functions.

1. To access the project using IAR IDE, open an MC workspace (FreeRTOS based or not) and click the name in the workspace tabbed browser (callout1, *Figure 80*). Remember

that IDE toolbars and commands always refer to the active project (the one whose tab is engraved).

Figure 80 displays the logical arrangement of files on the left-hand side (similar arrangement is in folders). For each class, the subfolder **src** contains the source code, **private** contains its private definitions, **interface** contains its public interface, **obj** contains compiled object files of certain classes.

Figure 80. MC Library project in IAR EWARM IDE



2. Depending on system characteristics, configure the project for single motor drive or dual motor drive by selecting SINGLE_DRIVE or DUAL_DRIVE from the combo-box (callout 2, *Figure 80*).
3. Classes of the MC Library can create new objects resorting to dynamic memory allocation, or statically allotting them from predefined size-pools. This is a matter of preference. Modify the header file MCLibraryConf.h to choose the allocation (callout 3, *Figure 80*). To activate the dynamic allocation, uncomment line 52 (#define

MC_CLASS_DYNAMIC). To activate the static allocation, comment this line.

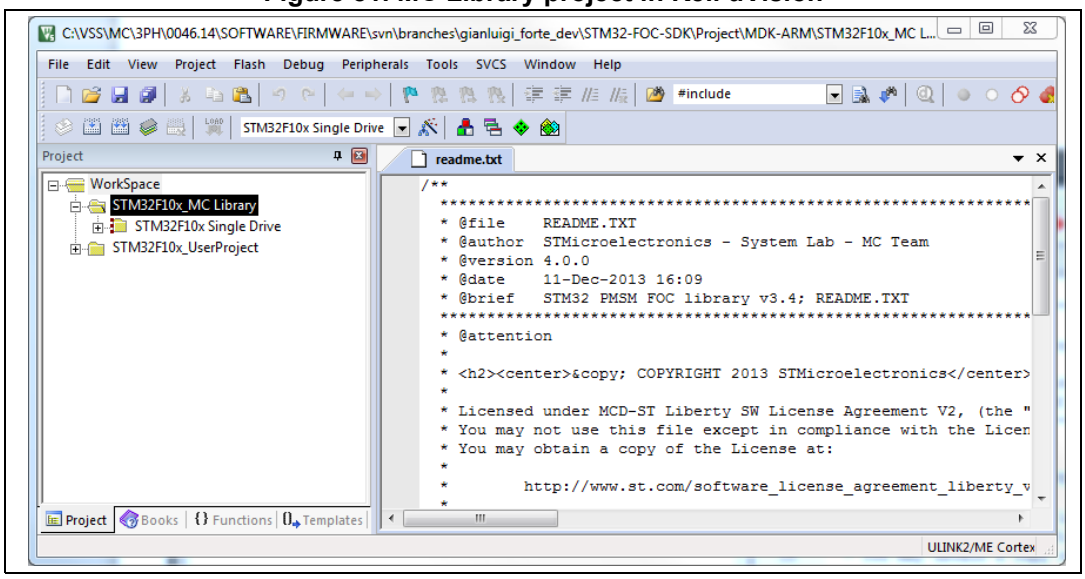
4. Once all these settings have been configured and checked, build the library (callout 4, *Figure 80*).
   If SINGLE_DRIVE was selected, the proper output file among the following:
   - MC_Library_STM32F0xx_single_drive.a
   - MC_Library_STM32F10x_single_drive.a
   - MC_Library_STM32F2xx_single_drive.a
   - MC_Library_STM32F303_single_drive.a
   - MC_Library_STM32F4xx_single_drive.a
   - MC_Library_STM32F302_single_drive.a
   - MC_Library_STM32F302x8_single_drive.a

   is created in `Installation folder \Project\EWARM\MCLibrary Compiled\Exe` or `Installation folder \FreeRTOSProject\EWARM\MC Library Compiled\Exe.`

   If DUAL_DRIVE was selected, the proper output file among the following:
   - MC_Library_STM32F10x_dual_drive.a
   - MC_Library_STM32F2xx_dual_drive.a
   - MC_Library_STM32F303_dual_drive.a
   - MC_Library_STM32F4xx_dual_drive.a
     is created in `Installation folder \Project\EWARM\MCLibrary Compiled\Exe` or `Installation folder \FreeRTOSProject\EWARM \MCLibrary Compiled\Exe`.
5. Compliancy with MISRA-C rules 2004 can be checked using IAR EWARM. The test is performed by uncommenting line 47(#define MISRA_C_2004_BUILD) in the header file Installation folder `\MCLibrary\Interface\Common\MC_type.h`. The compiler should be configured in Strict ISO/ANSI standard C mode (MISRA C 2004 rule 1.1).

Figure 81 shows the MC Library project in the Keil uVision IDE.

Figure 81. MC Library project in Keil uVision


File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
STM32F10x Single Drive
Project
WorkSpace
STM32F10x_MC Library
STM32F10x Single Drive
STM32F10x_UserProject
readme.txt
* @file README.TXT
* @author STMicroelectronics - System Lab - MC Team
* @version 4.0.0
* @date 11-Dec-2013 16:09
* @brief STM32 PMSM FOC library v3.4; README.TXT
* @attention
* Licensed under MCD-ST Liberty SW License Agreement V2, (the "
* You may not use this file except in compliance with the Licen
* You may obtain a copy of the License at:
http://www.st.com/software_license_agreement_liberty_v
Project Books Functions Templates
ULINK2/ME Cortex

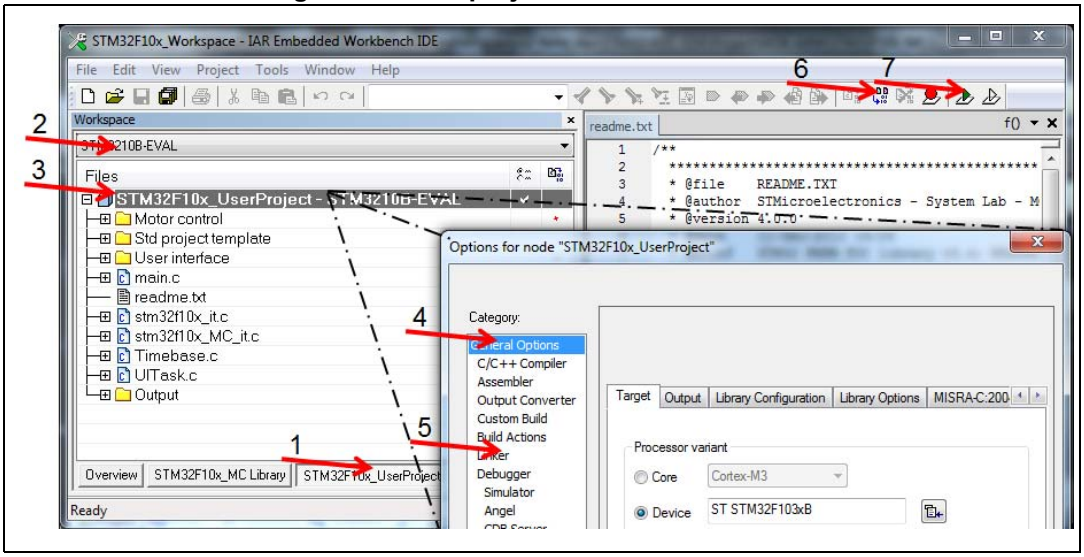
9.4 User project

The User project is the application layer that exploits the MC API.

1. Access the project using IAR IDE by opening an MC workspace (FreeRTOS based or not), and clicking its name in the workspace tabbed browser (callout 1, *Figure 82*). Remember that IDE toolbars and commands always refer to the active project (the one whose tab is engraved).

   Figure 82 displays the logical arrangement of files and actions necessary to set up and download the User project.

Figure 82. User project for IAR EWARM IDE



The Motor Control folder contains the MC API and interfaces of classes that may also be useful in the user's application (such as PI, Digital Output, reference frame transformation).

The Std project template folder contains:

- STM32Fxxx Standard Peripherals Library
- CMSIS library, startup and vector table files for EWARMv5 toolchain
- IC drivers (LCD, IOE, SD card) used in STM32 evaluation boards.

All these files belong to V3.5.0 distribution of the STM32 Standard Peripheral Library package for the STM32F10x and to v1.0.0 distribution for STM32F0xx, STM32F2xx, STM32F3xx and STM32F4xx (updates available from STMicroelectronics web site, www.st.com).

This demonstration user project exploits the features offered by the User Interface Library (see *Section 13: User Interface class overview* for further details).

In the STM32Fxxx_Workspace, the following project configurations (callout 2, *Figure 82: User project for IAR EWARM IDE*) are provided, one for each STM32 evaluation board that has been tested with the MC SDK:

- STM32F10B-EVAL
- STM32F10E-EVAL
- STM32F100B-EVAL
- STEVAL-IHM022V1_SINGLEDRIVE
- STEVAL-IHM022V1_DUALDRIVE
- STM322xG-EVAL
- STM32F2xx_dual
- STM32303C-EVAL_SINGLEDRIVE
- STM32303C-EVAL_DUALDRIVE
- STM32F302_SINGLEDRIVE
- STM324xG-EVAL
- STEVAL-IHM039V1_SINGLEDRIVE
- STEVAL-IHM039V1_DUALDRIVE
- P-NUCLEO-IHM001_SINGLEDRIVE

If the target is one of these boards, just select its name from the combo-box. Otherwise, the LCD UI should be disabled (using the ST MC Workbench GUI) and the choice is to be done according to *Table 13*:

Table 13. Project configurations

STM32 device part, single/dual drive selection	Viable configuration among existing
STM32F0xx, Single motor drive	STM320518-EVAL
STM32F103 low density/medium density	STM3210B-EVAL
STM32F103 high density/XL density, Single motor drive	STM3210E-EVAL or STEVAL-IHM022V1_SINGLEDRIVE
STM32F103 high density/XL density, Dual motor drive	STEVAL-IHM022V1_DUALDRIVE
STM32F100 low / medium / high density	STM32100B-EVAL
STM32F2xx, Single motor drive	STM322xG-EVAL
STM32F2xx, Dual motor drive	STM32F2xx_dual
STM32F303xB/C, Single motor drive	STM32303C-EVAL_SINGLEDRIVE
STM32F303xB/C, Dual motor drive	STM32303C-EVAL_DUALDRIVE
STM32F302xB/C, Single motor drive	STM32302C_SINGLEDRIVE
STM32F302x6/8, Single motor drive	P-NUCLEO-IHM001_SINGLEDRIVE
STM32F4xx, Single motor drive	STM324xG-EVAL STEVAL-IHM039V1_SINGLEDRIVE
STM32F4xx, Dual motor drive	STEVAL-IHM039V1_DUALDRIVE

If the target is not one of the above-mentioned ST evaluation boards, or if you want to modify the configurations provided, right-click on **User Project** (callout 3, *Figure 82*) >

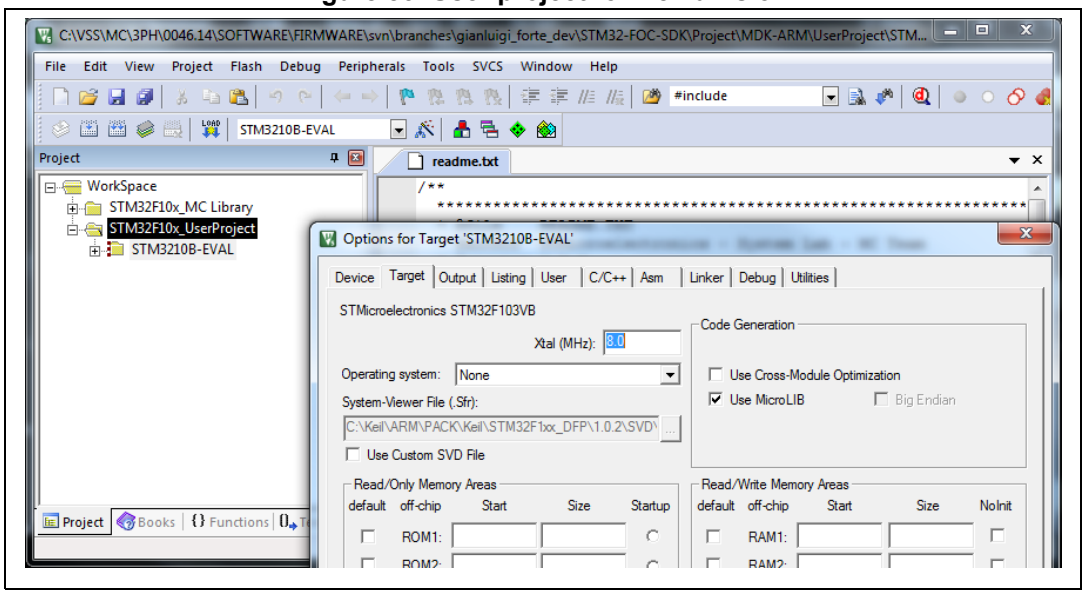
Option to open the **Options** dialog box. Select the correct device part number (callout 4, *Figure 82*) and edit the linker file (callout 5, *Figure 82*).

Note: MC SDK default linker files reserve an amount of Flash and RAM (heap) for LCD UI manager (see Section 9.4). We recommend that you restore their total size (please refer to the STM32 datasheet) if you do not need it.

Once all these settings have been performed, the MC Library and MC Application projects are built and you can build the user project (callout 6, *Figure 82*), and download it to the microcontroller memory (callout 7, *Figure 82*).

The same considerations can be done for Keil uVision user project shown in *Figure 83*.

Figure 83. User project for Keil uVision



9.5 Full LCD UI project

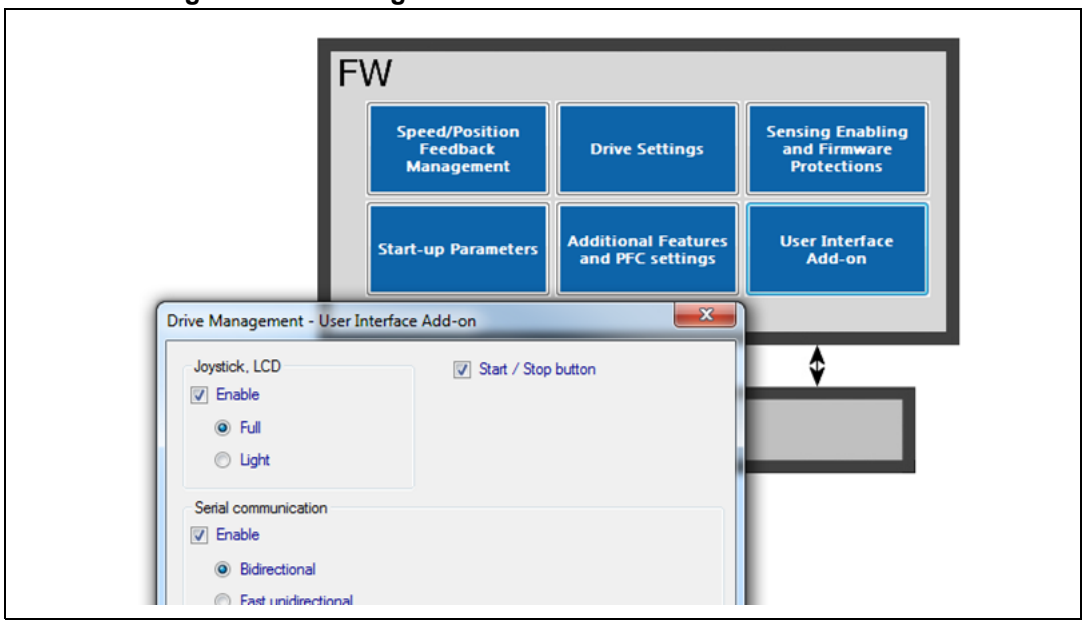
When an STM32 evaluation board equipped with LCD (such as STM3210B-EVAL, STM3210E-EVAL, STM32100B-EVAL, STEVAL-IHM022V1, STM322xG-EVAL, STM324xG-EVAL, STEVAL-IHM039V1, STM32303C-EVAL) is in use, you can enable the LCD plus Joystick User Interface—a useful feature of the demonstration user project that can be used as a run-time command launcher, a fine-tuning or monitoring tool (screens and functions are detailed in *Section 11*). This option can be selected via a setting in the ST MC Workbench GUI (see *Figure 84*).

In this case, the LCD UI software (single or dual drive configuration) is downloaded in the microcontroller in a reserved area, located at the end of the addressable Flash memory. Unless you erase it or change the configuration from single-drive to dual-drive or vice-versa, there is no need to download it again. Even disabling the option with the GUI does not mean you need to flash it again when you reenable the option.

The latest STM3210B-MCKIT Motor Control starter kits come with the Motor Control Library and the LCD UI software (single-drive) pre-flashed. If your Motor Control kit has a version of Motor Control Library lower than 3.4, or if you do not have the Motor Control kit but you are

using one of the evaluation boards mentioned, or if you are changing the configuration (single-dual), you should follow one of the three procedures explained below to download the LCD UI.

Figure 84. Enabling the Full LCD UI in the ST MC Workbench



Option 1

Option 1 is straightforward and the preferred one.

- Use the STM32 ST-LINK Utility tool to download the LCD pre-compiled file.
- Activate File ->Open file.
- Select the appropriate pre-compiled file (STM3210B-EVAL.hex, STM32100B-EVAL.hex, STM3210E-EVAL.hex, STEVAL-IHM022V1_SINGLEDRIVE.hex, STEVAL-IHM022V1_DUALDRIVE.hex, STM322xG-EVAL.hex, STM324xG-EVAL.hex, STEVAL-IHM039V1_SINGLEDRIVE.hex, STEVAL-IHM039V1_DUALDRIVE.hex, STM32303C-EVAL_SINGLEDRIVE.hex, STM32303C-EVAL_DUALDRIVE.hex)

Option 2

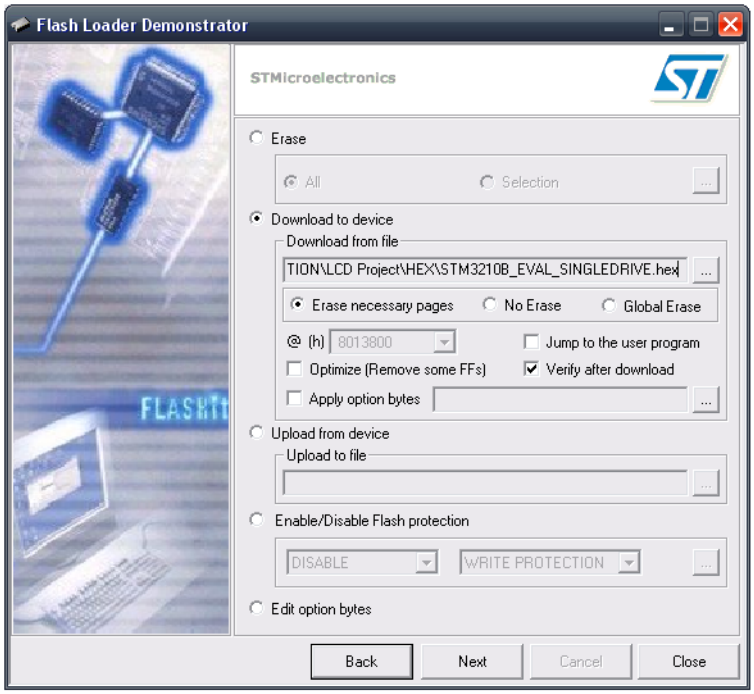
1. Use the STM32 and STM8 Flash loader demonstrator PC software package. This is available from the ST web site (www.st.com).

   The User Manual, UM0462 (included in the package), fully explains how to operate it. For communication purposes, you need to verify that you have an available COM port (RS232) on your PC.
2. After the program is installed, run the Flash loader demonstrator application from the Programs menu, making sure that the device is connected to your PC and that the boot configuration pins are set correctly to boot from the system memory (check the evaluation board user manual).
3. Reset the microcontroller to restart the system memory boot loader code.
4. When the connection is established, the wizard displays the available device information such as the target ID, the firmware version, the supported device, the

memory map and the memory protection status. Select the target name in the target combo-box.

5. Click the **Download to device** radio button (see *Figure 85*) and browse to select the appropriate hexadecimal file (STM3210B_EVAL.hex, STM32100B_EVAL.hex, STM3210E_EVAL.hex, STEVAL_IHM022V1_SINGLEDRIVE.hex, STEVAL_IHM022V1_DUALDRIVE.hex, STM322xG-EVAL.hex, STM324xG-EVAL.hex, STEVAL_IHM039V1_SINGLEDRIVE.hex or STEVAL_IHM039V1_DUALDRIVE.hex) from Installation folder\LCD Project\Hex\.
6. Program the downloading to Flash memory. After the code has been successfully flashed, set up the board to reboot from the user Flash memory and reset the microcontroller.
7. To test that the LCD UI has been correctly flashed, for both option 1 and 2, open, build and download the user project (see *Section 9.2: MC SDK customization process* and *Section 9.4: User project*).
8. From the debug session, run the firmware (**F5**) and then, after a while, stop debugging (CTRL+Shift+D). The LCD UI has not been properly flashed if the program is stalled in a trap inside UITask.c, line 195.

Figure 85. Flash loader wizard screen



Option 3

This option is intended for users who want to modify the LCD UI code.

1. Use an IDE to rebuild and download the LCD UI.
2. After parameter files have been generated by the GUI (to set the single/dual drive configuration) using KEIL uVision4 IDE, open the workspace located in

```
Installation folder\LCDProject\MDK-ARM\STM32F0xx_LCD Project.uvopt
Installation folder\LCDProject\MDK-ARM\STM32F10x_LCD Project.uvopt
```

```
Installation folder\LCDProject\MDK-ARM\STM32F2xx_LCD Project.uvopt
Installation folder\LCDProject\MDK-ARM\STM32F3xx_LCD Project.uvopt
Installation folder\LCDProject\MDK-ARM\STM32F4xx_LCD Project.uvopt
```

Figure 86. LCD UI project

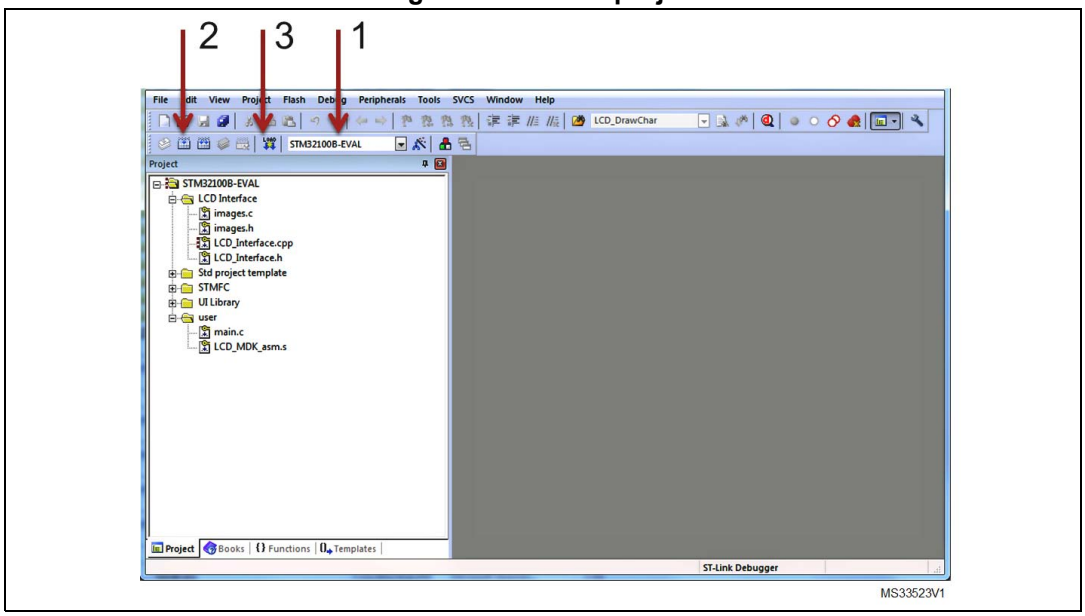


Figure 86 displays the logical arrangement of files (left-hand side) and actions that may be needed for set-up and download.

Following project configurations are provided for the STM32Fxxx_Workspace (callout 1, *Figure 86*), one for each STM32 evaluation board that has been tested with the MC SDK:

- STM32F100B-EVAL
- STM32F10B-EVAL
- STM32F10E-EVAL
- STEVAL-IHM022V1_SINGLEDRIVE
- STEVAL-IHM022V1_DUALDRIVE
- STM322xG-EVAL
- STM32303C-EVAL_SINGLEDRIVE
- .....
- STM324xG-EVAL
- STEVAL-IHM039V1_SINGLEDRIVE
- STEVAL-IHM039V1_DUALDRIVE

This configuration affects the LCD driver and linker file selection.

3. Build the project (callout 2, *Figure 86*), and download it to the microcontroller memory (callout 3, *Figure 86*).
4. To test that the LCD UI has been correctly flashed, for both option 1 and 2, open, build and download the user project (see *Section 9.2: MC SDK customization process* and

Section 9.4: User project).

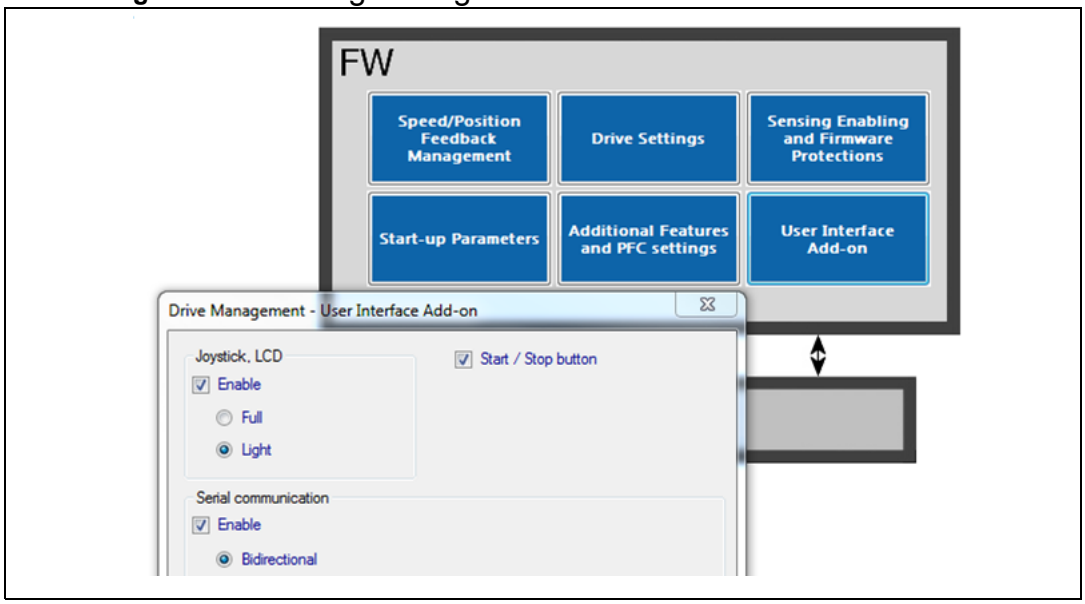
5. From the debug session, run the firmware (**F5**) and then, after a while, stop debugging (CTRL+Shift+D). The LCD UI has not been properly flashed if the program is stalled in a trap in UITask.c, line 195.

9.6 Light LCD UI

Together with the User project is provided a simplified version of LCD user interface that can be used together with a STM32 evaluation board equipped with LCD (such as STM3210B-EVAL, STM3210E-EVAL, STM32100B-EVAL, STEVAL-IHM022V1, STM322xG-EVAL, STM324xG-EVAL, STEVAL-IHM039V1, STM32303C-EVAL) (screens and functions are detailed in *Section 12*). This option can be selected via a setting in the ST MC Workbench GUI (*Figure 87*).

Enabling this option is not necessary to flash the LCD FW code as explained in the previous paragraph.

Figure 87. Enabling the Light LCD UI in the ST MC Workbench



10 MC application programming interface (API)

The Motor Control Application is built on top of the Motor Control Library, provided that:

- parameter files are generated by the ST MC workbench GUI, or manually edited starting from default, for the purpose of describing the system configuration;
- a user project, such as the one included in the SDK, or any other one that complies with the guidelines described in *Section 10.3: How to create a user project that interacts with the MC API*, is in place.

The MCA grants the user layer the execution of a set of commands, named the MC Application Programming Interface (MC API).

The MC API is divided into two sections and is included in two files: MCInterfaceClass.h and MCTuningClass.h. MCInterfaceClass (details in *Section 10.1*) holds the principal high-level commands, while MCTuningClass (details in *Section 10.2*) acts as a gateway to set and read data to and from objects (such as sensors, PI controllers) belonging to the Motor Control Application.

A third section belongs to MC API, MCtask.h: it holds the MCboot function and tasks (medium/high frequency and safety) to be clocked by the user project (see *Section 10.3: How to create a user project that interacts with the MC API* for details)

When the user project calls function MCboot (oMCI, oMCT), the Motor Control Application starts its operations: the booting process begins, objects are created from the Motor Control Library according to the system configuration (specified in parameter files), and the application is up and represented by two objects, oMCI and oMCT, whose type is respectively CMCI and CMCT (type definition can be obtained by including MCInterfaceClass.h and MCTuningClass.h). Methods of MCInterfaceClass must be addressed to the oMCI object, oMCT addresses methods of MCTuningClass. oMCI and oMCT are two arrays, each of two elements, so that oMCI[0] and oMCT[0] refer to Motor 1, oMCI[1] and oMCT[1] refer to Motor2.

GetMCIList function, to be called if necessary after MCboot, returns a pointer to the CMCI oMCI vector instantiated by MCboot. The vector has a length equal to the number of motor drives.

GetMCTList function, to be called if necessary after MCboot, returns a pointer to the CMCT oMCT vector instantiated by MCboot. The vector has a length equal to the number of motor drives.

10.1 MCInterfaceClass

Commands of the MCInterfaceClass can be grouped in two different typologies:

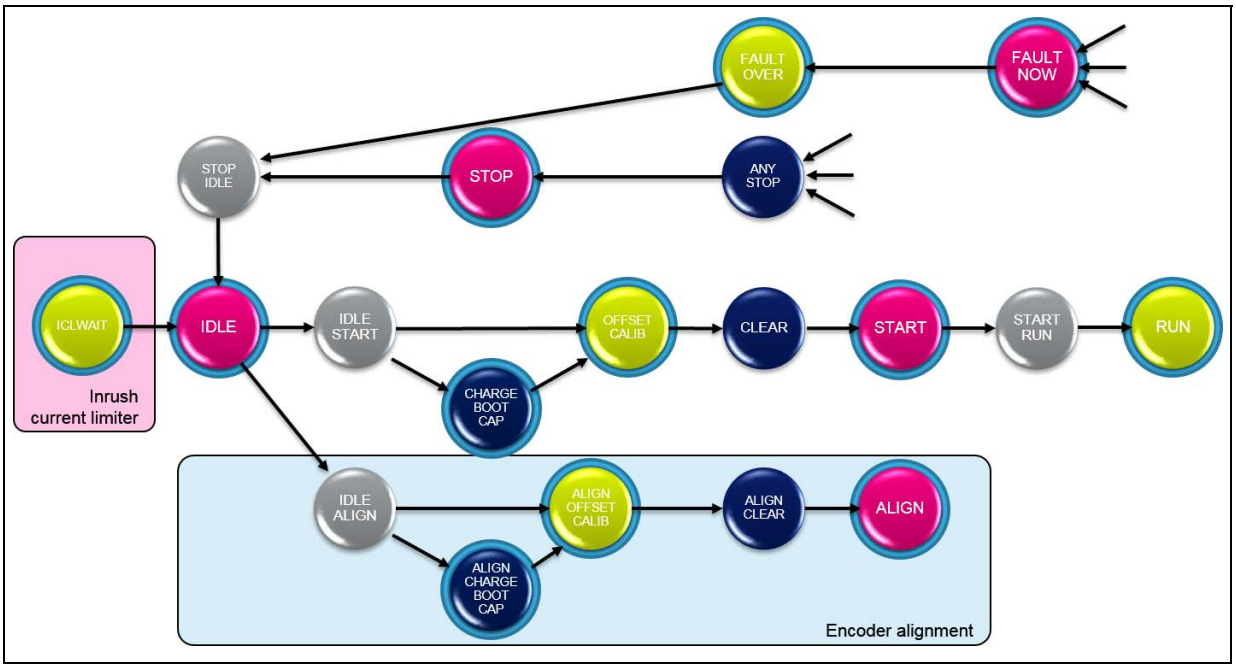
- User commands: commands that become active as soon as they are called. If the state machine is not in the expected state, the command is discarded and the method returns FALSE. The user must manage this by resending the command until it is accepted, or by discarding the command.
- Buffered commands: commands that do not execute instantaneously, but are stored in a buffer and become active when the state machine is in a specified state. These commands are not discarded until they become active, unless other delayed commands are sent to the buffer, thus clearing the previous one.

Detailed information can be found in the Motor Control Application source documentation (doxygen compiled .html Help file).

10.1.1 User commands

- `bool MCI_StartMotor(CMCI oMCI)`: starts the motor. It is mandatory to set the target control mode (speed control/torque control) and initial reference before executing this command, otherwise the behavior in run state is unpredictable. Use one of these commands to do this: MCI_ExecSpeedRamp, MCI_ExecTorqueRamp or MCI_SetCurrentReferences.
- `bool MCI_StopMotor(CMCI oMCI)`: stops the motor driving and disables the PWM outputs.
- `bool MCI_FaultAcknowledged(CMCI oMCI)`: this function must be called after a system fault to tell the Motor Control Interface that the user has acknowledged the occurred fault. When a malfunction (overcurrent, overvoltage) is detected by the application, the motor is stopped and the internal state machine goes to the Fault state (see *Figure 88*). The API is locked (it no longer receives commands). The API is unlocked and the state machine returns to Idle when the user sends this MCI_FaultAcknowledged.
- `bool MCI_EncoderAlign(CMCI oMCI)`: this function is only used when an encoder speed sensor is used. It must be called after any system reset and before the first motor start.
- `State_t MCI_GetSTMState(CMCI oMCI)`: returns the state machine status (see *Figure 88*). Further detail is provided in the *Advanced developers guide for STM32F0x/F100xx/F103xx/STM32F2xx/F30x/F4xx MCUs PMSM single/dual FOC library* (UM1053).

Figure 88. State machine flow diagram



- `int16_t MCI_GetMecSpeedRef01Hz(CMCI oMCI)`: returns the current mechanical rotor speed reference expressed in tenths of Hertz.
- `int16_t MCI_GetAvrgMecSpeed01Hz(CMCI oMCI)`: returns the last computed average mechanical speed expressed in tenth of Hertz.
- `int16_t MCI_GetTorqueRef(CMCI oMCI)`: returns the present motor torque reference. This value represents the I_q current reference expressed in 's16A'. To convert a current expressed in 's16A' to a current expressed in Ampere, use the formula:

  ```
  Current[A] = [Current(s16A) * Vdd micro(V)] / [65536 *
  Rshunt(Ohm) * AmplificationNetworkGain]
  ```

- `int16_t MCI_GetTorque(CMCI oMCI)`: returns the present motor measured torque. This value represents the I_q current expressed in 's16A'. To convert a current expressed in 's16A' to current expressed in Ampere, use the formula:

  ```
  Current[A] = [Current(s16A) * Vdd micro(V)] / [65536 *
  Rshunt(Ohm) * AmplificationNetworkGain]
  ```

- `Curr_Components MCI_GetCurrentsReference(CMCI oMCI)`: returns stator current references I_q and Id in 's16A'. To convert a current expressed in 's16A' to a current expressed in Ampere, use the formula:

  ```
  Current[A] = [Current(s16A) * Vdd micro(V)] / [65536 *
  Rshunt(Ohm) * AmplificationNetworkGain].
  ```

- `int16_t MCI_GetPhaseCurrentAmplitude(CMCI oMCI)`: returns the motor phase current amplitude (0-to-peak) in 's16A'. To convert a current expressed in 's16A' to a current expressed in Ampere, use the formula:

  ```
  Current[A] = [Current(s16A) * Vdd micro(V)] / [65536 *
  Rshunt(Ohm) * AmplificationNetworkGain].
  ```

- `int16_t MCI_GetPhaseVoltageAmplitude(CMCI oMCI)`: returns the applied motor phase voltage amplitude (0-to-peak) in 's16V'. To convert a voltage expressed in 's16V' to a voltage expressed in Volt, use the formula:

  ```
  PhaseVoltage(V) = [PhaseVoltage(s16V) * Vbus(V)] /[sqrt(3)
  *32767].
  ```

- `STC_Modality_t MCI_GetControlMode(CMCI oMCI)`: returns the present control mode: speed mode or torque mode.
- `int16_t MCI_GetImposedMotorDirection(CMCI oMCI)`: returns the motor direction imposed by the last command (MCI_ExecSpeedRamp, MCI_ExecTorqueRamp or MCI_SetCurrentReferences).
- `int16_t MCI_GetLastRampFinalSpeed (CMCI this)`: returns information about the last ramp final speed sent by the user, expressed in tenths of HZ.

10.1.2 Buffered commands

- `void MCI_ExecSpeedRamp(CMCI oMCI, int16_t hFinalSpeed, uint16_t hDurationms)`: sets the control mode in speed control, generates a ramp of speed references from real speed to hFinalSpeed parameter (to be expressed as mechanical rotor speed, tenth of hertz). The ramp execution duration is the ‘hDurationms’ parameter (to be expressed in milliseconds). If hDurationms is set to 0, a step variation is generated. This command is only executed when the state machine is in the

START_RUN or RUN state. The user can check the status of the command calling the MCI_IsCommandAcknowledged method.

- `void MCI_ExecTorqueRamp(CMCI oMCI, int16_t hFinalTorque, uint16_t hDurationms)`: sets the control mode in "torque control", generates a ramp of torque references from real torque to the 'hFinalTorque' parameter (to be expressed as s16A). The ramp execution duration is the hDurationms parameter (to be expressed in milliseconds). If hDurationms is set to 0, a step variation is generated. This command is only executed when the state machine is in the **START_RUN** or **RUN** state. The user can check the status of the command calling the MCI_IsCommandAcknowledged method.
- `void MCI_SetCurrentReferences(CMCI oMCI, Curr_Components Iqdref)`: sets the control mode in "torque control external" (see *Advanced developers guide for STM32F0x/F100xx/F103xx/STM32F2xx/F30x/F4xx MCUs PMSM single/dual FOC library* (UM1053)) and directly sets the motor current references I_q and I_d (to be expressed as s16A). This command is only executed when the state machine status is **START_RUN** or **RUN**.
- `CommandState_t MCI_IsCommandAcknowledged(CMCI oMCI)`: returns information about the state of the last buffered command. CommandState_t can be one of the following codes:
  - `MCI_BUFFER_EMPTY` if no buffered command has been called.
  - `MCI_COMMAND_NOT_ALREADY_EXECUTED` if the buffered command condition has not already occurred.
  - `MCI_COMMAND_EXECUTED_SUCCESFULLY` if the buffered command has been executed successfully. In this case, calling this function resets the command state to `MCI_BUFFER_EMPTY`.
  - `MCI_COMMAND_EXECUTED_UNSUCCESFULLY` if the buffered command has been executed unsuccessfully. In this case, calling this function resets the command state to `MCI_BUFFER_EMPTY`.

10.2 MCTuningClass

The MCTuningClass allows the user to obtain objects of the Motor Control Application and apply methods on them.

MCTuningClass.h is divided into three sections:

- Public definitions of all the MC classes exported
- MCT_GetXXX functions, used to receive objects
- For each of the classes exported, a list of applicable methods

For example, if you want to read or set parameters of the speed PI controller:

1. Make sure that the Motor Control Application is already booted, and oMCI and oMCT objects are available (you can receive them through GetMCIList or GetMCTList functions)
2. Declare a 'PIspeed' automatic variable of the type CPI (PI class, type definition at line 92)
3. Obtain the speed PI object (which is actually a pointer) by calling the MCT_GetSpeedLoopPID function (prototype at line 210)
4. Set the KP gain by calling the PI_SetKP function (prototype at line 708).

   The resulting C code could be something like:

```
#include "MCTuningClass.h"
{
...
CPI PIspeedMotor2;
...
PIspeedMotor2 = MCT_GetSpeedLoopPID(oMCT[1]);
PI_SetKP(PIspeedMotor2, NewKpGain);
...
}
```

Note: 1 To reduce Flash and RAM occupation, you can disable the MCTuning section of the MC application. This is done by commenting #define MC_TUNING_INTERFACE in the MCTask.c source file, line 90. If you do this, disable the LCD UI and Serial Communication UI too.

2 See the doxygen compiled .html Help file to know which are the other exported functions of MCTasks and refer to section 7.3 to know how to use them.

10.3 How to create a user project that interacts with the MC API

This section explains how to integrate the Motor Control Application with a user project (thus replacing the provided demonstrative one) in order to take advantage of its API.

1. A timebase is needed to clock the MC Application: the demonstration timebase.c can be considered as an example or used as is. It uses the Systick timer and its Systick_Handler and PendSV_Handler as resources.

   Alternatively, an Operating System can be used for this purpose, as is done in the FreeRTOS-based demonstration project.

   The timebase should provide the clocks listed in *Table 14*:

Table 14. Integrating the MC Interface in a user project

Number	Function to call	Periodicity	Priority	Preemptiveness
*1	`TSK_MediumFrequencyTask`	Equal to that set in ST MC Workbench, speed regulation rate	Systick priority	Yes, over non MC functions
*2	`TSK_SafetyTask`	0.5 ms	Higher than *1	optional over *1

2. Include source files:

Note: In the following code, $ stands for Installation Folder.

for STM32F0xx projects

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F0xx\Source\Template\system_stm32f0xx.c

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F0xx\Source\Template\XXX\startup_stm32f0xx.s (XXX according to IDE)

$\Project\stm32f0xx_it.c (removing conditional compilation, can be modified)

$\Project\SystemDriveParams\stm32f0xx_MC_it.c

$\Libraries\STM32F0xx_StdPeriph_Driver\src\ (standard peripheral driver sources as needed)

For STM32F1xx projects

$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F10x\system_stm32f10x.c

$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F10x\startup\XXX\startup_stm32f10x_YYY.s (XXX according to IDE)(YYY according to device)

$\Project\stm32f10x_it.c (removing conditional compilation, can be modified) $\Project\SystemDriveParams\stm32f10x_MC_it.c (GUI generated according to system parameters)

$\Libraries\STM32F10x_StdPeriph_Driver\src\ (standard peripheral driver sources as needed)

for STM32F2xx projects

$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F2xx\system_stm32f2xx.c

$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F2xx\startup\XXX\startup_stm32f2xx.s (XXX according to IDE)

$\Project\stm32f2xx_it.c (removing conditional compilation, can be modified)

$\Project\SystemDriveParams\stm32f2xx_MC_it.c (GUI generated according to system parameters)

$\Libraries\STM32F2xx_StdPeriph_Driver\src\ (standard peripheral driver sources as needed)

for STM32F3xx projects

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F30x\Source\Template\system_stm

32f30x.c

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F30x\Source\Template\XXX\startup_stm32f302.s or startup_stm32f303.s (XXX according to IDE)

$\Project\stm32f30x_it.c (removing conditional compilation, can be modified)

$\Project\SystemDriveParams\stm32f30x_MC_it.c (GUI generated according to system parameters)

$\Libraries\STM32F30x_StdPeriph_Driver\src\ (standard peripheral driver sources as needed)

for STM32F4xx projects

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F4xx\Source\Templatesystem_stm32f4xx.c

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F4xx\Source\Templates\XXX\startup_stm32f4xx.s (XXX according to IDE)

$\Project\stm32f4xx_it.c (removing conditional compilation, can be modified)

$\Project\SystemDriveParams\stm32f4xx_MC_it.c (GUI generated according to system parameters)

$\Libraries\STM32F4xx_StdPeriph_Driver\src\ (standard peripheral driver sources as needed)

3. Include paths:

Note: In the following code, $ stands for Installation Folder.

for STM32F0xx projects

$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F0xx\Include

$\Libraries\STM32F0xx_StdPeriph_Driver\inc

$\MClibrary\interface\common\

$\MCApplication\interface\

$\SystemDrive Params\

$\Project\

for STM32F1xx projects

```
$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F10x\
$\Libraries\STM32F10x_StdPeriph_Driver\inc\
$\MClibrary\interface\common\
$\MCApplication\interface\
$\SystemDriveParams\
$\Project\
```

for STM32F2xx projects

$\Libraries\CMSIS\CM3\DeviceSupport\ST\STM32F2xx

$\Libraries\STM32F2xx_StdPeriph_Driver\inc

$\MClibrary\interface\common\

$\MCApplication\interface\

$\SystemDriveParams\
$\Project\

for STM32F30x projects
$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F30x\Include
$\Libraries\STM32F30x_StdPeriph_Driver\inc
$\MCLibrary\interface\common\
$\MCApplication\interface\
$\SystemDriveParams\
$\Project\

for STM32F4xx projects
$\Libraries\CMSIS\CMSIS_2_x\Device\ST\STM32F4xx\Include
$\Libraries\STM32F4xx_StdPeriph_Driver\inc
$\MClibrary\interface\common\
$\MCApplication\interface\
$\SystemDriveParams\
$\Project\

4. Include libraries:

(if in single motor drive) Select the proper libraries according to the microcontroller family:
*\MC Library Compiled\Exe\MC_Library_STM32F0xx_single_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F10x_single_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F2xx_single_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F303_single_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F302_single_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F4xx_single_drive.a

(if in dual motor drive) Select the proper libraries according to the microcontroller family:
*\MC Library Compiled\Exe\MC_Library_STM32F10x_dual_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F2xx_dual_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F303_dual_drive.a
*\MC Library Compiled\Exe\MC_Library_STM32F4xx_dual_drive.a

Select the proper libraries according to the microcontroller family:
**\MC Application Compiled\Exe\MC_Application_STM32F0xx.a
**\MC Application Compiled\Exe\MC_Application_STM32F10x.a
**\MC Application Compiled\Exe\MC_Application_STM32F2xx.a
**\MC Application Compiled\Exe\MC_Application_STM32F30x.a

**\MC Application Compiled\Exe\MC_Application_STM32F4xx.a

```
* is the path where the MCLibrary IDE project is located
** is the path where the MCApplication IDE project is located
```

5. Define symbols:

   ```
   USE_STDPERIPH_DRIVER
   STM32F0XX \ STM32F10X_MD \ STM32F10X_HD \ STM32F10X_MD_VL \
   STM32F2XX, STM32F30X, STM32F40X(according to STM32 part)
   ```

6. Set the STM32 NVIC (Nested Vectored Interrupt Controller) priority group configuration (the default option is NVIC_PriorityGroup_3).

   ```
   NVIC_PriorityGroupConfig(NVIC_PriorityGroup_3);
   ```

   Table 15 shows preemption priorities used by the MC application; user priorities should be lower (higher number):

Table 15. MC application preemption priorities

IRQ	Preemption priority
TIM1 UPDATE	0
TIM8 UPDATE (F103HD/XL, F2xx, F30x, F4xx)	0
DMA	0
ADC1_2 (F103, F2xx, F30x, F4xx)	2
ADC1 (F0xx)	1
ADC3 (F103HD/XL, F2xx, F30x, F4xx)	2
ADC4 (F30x only)	2
ADC1 (F100 only)	2
USART (UI library)	3
USART (UI library for F0xx)	3
TIMx GLOBAL (speed sensor decoding)	3
TIMx GLOBAL (speed sensor decoding for F0xx)	2
Timebase	>3
Timebase (Systick for F0xx)	2
Timebase (PendSV for F0xx)	3
Hard Fault	-1 (fixed by core architecture)

Table 16. Priority configuration, overall (non FreeRTOS)

Component	Preemption priority
MC Library	0,1,2,3
Timebase (MCA clocks)	3,4

Table 16. Priority configuration, overall (non FreeRTOS)

Component	Preemption priority
Timebase (MCA clocks for F0xx)	2,3
User	5,6,7
User (F0xx)	3

Table 17. Priority configuration, overall (FreeRTOS)

Component	Preemption priority	
MC Library	0,1,2,3	
User (only FreeRTOS API)	4,5	
FreeRTOS	6,7	RTOS priority
	MCA clock tasks	Highest
	User tasks	Lower

7. Include the Motor Control Interface in the source files where the API is to be accessed:

```
#include "MCTuningClass.h"
#include "MCInterfaceClass.h"
#include "MCTasks.h"
```

8. Declare a static array of CMCI (MC Interface class) type:

```
CMCI oMCI[MC_NUM]; /* MC_NUM is the number of motors to drive*/
```

9. Declare a static array of CMCT (MC Tuning class) type:

```
CMCT oMCT[MC_NUM]; /* MC_NUM is the number of motors to drive*/
```

10. Start the MC Interface boot process:

```
MCboot(oMCI,oMCT);
```

11. Send the command to the MC API. For example:

```
MCI_ExecSpeedRamp(oMCI[1],100,1000);
MCI_StartMotor(oMCI[1]);
... /* after a laps of time*/
MCI_StopMotor(oMCI[1]);
```

10.4 Measurement units

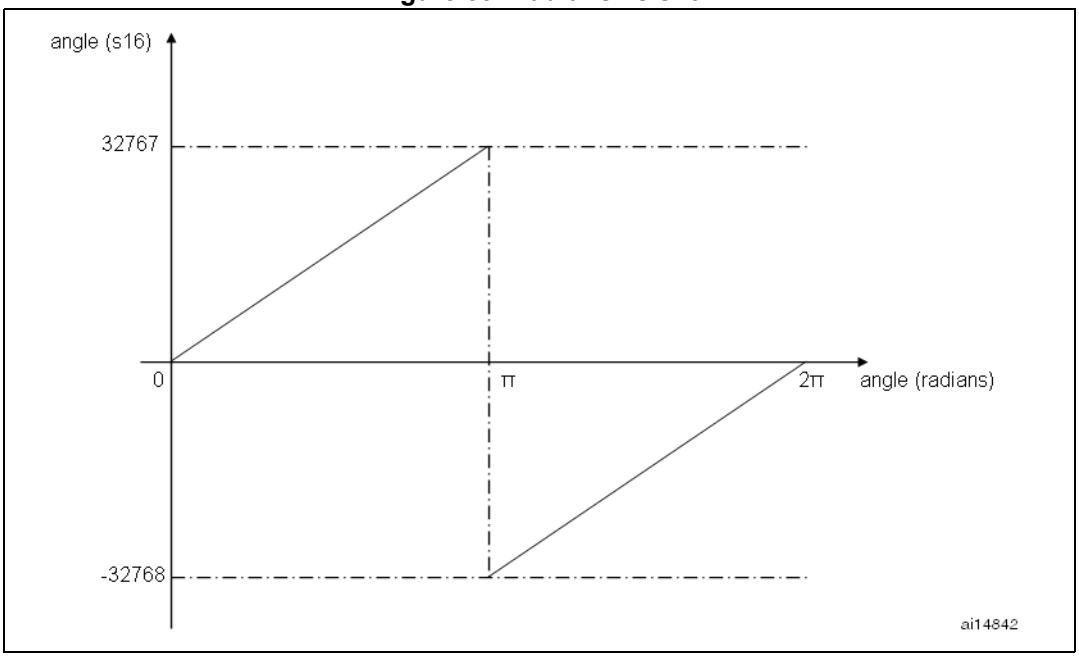
10.4.1 Rotor angle

The rotor angle measurement unit used in the MC API has been named 's16degrees', being

$$1s16degree = \frac{2\pi}{65536}$$

Figure 89 shows how an angle expressed in radians can be mapped into the s16degrees domain.

Figure 89. Radians vs s16



10.4.2 Rotor speed

The rotor speed units used in the MC API are:

- Tenth of Hertz (01Hz): straightforwardly, it is 01*Hz* = 0.1 *Hz*
- digit per control period (dpp): the dpp format expresses the angular speed as the variation of the electrical angle (expressed in s16 format) within a FOC period,

$$1dpp = \frac{1s16degree}{1FOCperiod}$$

An angular speed, expressed as the frequency in Tenth of Hertz (01Hz), can be easily converted to dpp using the formula:

$$\omega_{dpp} = \omega_{01Hz} \bullet \frac{65536}{10 \bullet FOCfreq_{Hz}}$$

10.4.3 Current measurement

Phase currents measurement unit used in the MC API has been named 's16A', being:

$$1s16A = \frac{MaxMeasureableCurrent_A}{32767}$$

A current, expressed in Ampere, can be easily converted to s16A, using the formula:

$$i_{s16A} = \frac{i_A \times 65536 \bullet RShunt_\Omega \times AmplificationGain}{\mu C\_VDD_v}$$

10.4.4 Voltage measurement

Applied phase voltage unit used in the MC API has been named 's16V', being:

$$1s16V = \frac{MaxApplicablePhaseVoltage_V}{32767}$$

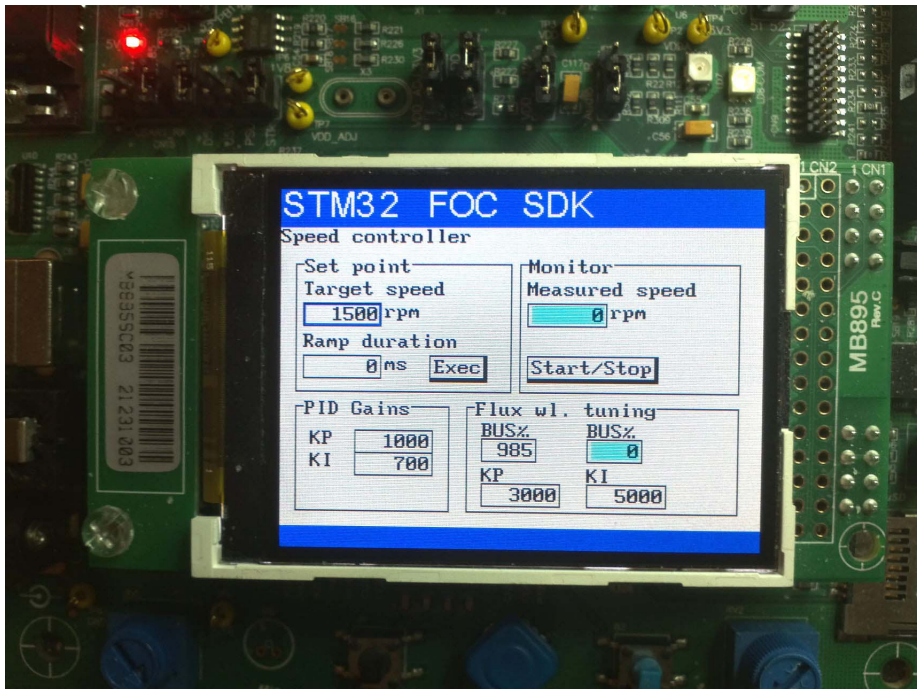
11 Full LCD user interface

11.1 Running the motor control firmware using the full LCD interface

The STM32 motor control library includes a demonstration program that enables you to display drive variables, customize the application by changing parameters, and enable and disable options in real time.

The user interface reference is the one present in the STM32 evaluation boards and is shown in *Figure 90*.

Figure 90. User interface reference



The interface is composed of:

- A 320x240 pixel color LCD screen
- A joystick (see *Table 18* for the list of joystick actions and conventions)
- A push-button (KEY button)

Table 18. Joystick actions and conventions

Keyword	User action
UP	Joystick pressed up
DOWN	Joystick pressed down
LEFT	Joystick pressed to the left
RIGHT	Joystick pressed to the right

Table 18. Joystick actions and conventions (continued)

Keyword	User action
JOYSEL	Joystick pushed
KEY	Press the KEY push-button

In the default firmware configuration, the LCD management is enabled. It can be disabled using the STM32 MC Workbench or disabling the feature and manually changing the line: `define #define LCD_JOYSTICK_BUTTON_FUNCTIONALITY DISABLE` (line 316) of the Drive parameters.h file.

The LCD management is provided by a separate workspace (UI Project) that should be compiled and programmed before the motor control firmware programming.

11.2 LCD User interface structure

The demonstration program is based on circular navigation pages.

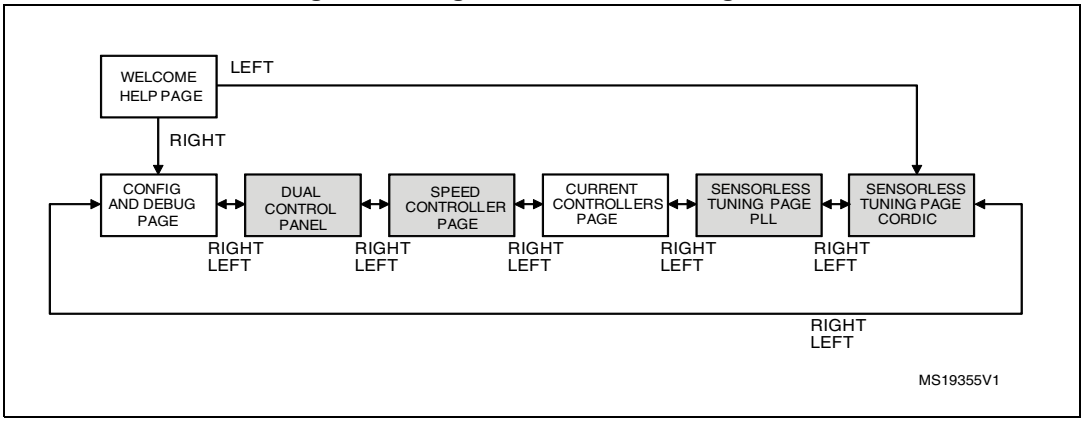
Figure 91 shows the page structure. The visibility of certain pages shown in *Figure 91* depends on the firmware configuration:

- Dual control panel is only present if the firmware is configured for dual motor drive.
- Speed controller page is only present when the firmware is configured in speed mode.
- Sensorless tuning page (PLL) is only present if the firmware is configured with state observer with PLL as primary or auxiliary speed sensor.
- Sensorless tuning page (CORDIC) is only present if the firmware is configured with state observer with CORDIC as primary or auxiliary speed sensor.

To navigate the help menus, use:

- RIGHT to navigate to the next page on the right
- LEFT to navigate to the next page on the left

Figure 91. Page structure and navigation



Each page is composed of a set of controls. *Table 19* presents the list of controls used in the LCD demonstration program.You can navigate between focusable controls in the page by pressing the UP and DOWN joystick. The focused control is highlighted with a blue rectangle. When focused, you can activate the control by pressing JOYSEL.

For some configurations such as STM32F100B-EVAL, a reduced set of LCD pages and/or controls is available.

Table 19. List of controls used in the LCD demonstration program

Control name and Example	Description
Edit box 1500 rpm	Manages a numerical value. It can be "read-only" or "read/write". A read-only edit box has a gray background and cannot be focusable. A read/write edit box has a white background and can be focusable. When a read/write edit box is focused, it can be activated for modification by pressing JOYSEL. An activated read/write edit box has a green background and its value can be modified pressing and/or keeping pressed the UP/DOWN joystick. When the UP joystick is kept pressed, the value is increased with a constant acceleration. When the DOWN joystick is kept pressed, the value is decreased with a constant acceleration. The new value is set to the motor control-related object instantaneously when the value changes, unless otherwise mentioned in this manual. The control can be deactivated by pressing JOYSEL again.
Combo-box Speed ▼	Manages a list of predefined values. The values associated to a combo-box are text strings that correspond with different configurations or options of the firmware. For example, Speed or Torque control mode. The combo-box is always focusable and, when focused, can be activated for modification by pressing JOYSEL. An activated combo-box has a green background and its value can be modified by pressing the UP/DOWN joystick. The combo-box values are circular. Going UP from the first value selects the last value and vice versa. The new value is set to the motor control-related object instantaneously when the value changes, unless otherwise mentioned in this manual. The control can be deactivated by pressing JOYSEL again.
Button Fault ack	Sends commands to motor control-related object. For example, a start/stop button. This button can be enabled or disabled. A disabled button is drawn in light gray and cannot be focusable. An enabled button is painted in black and can be focusable. When focused, a button can be activated by pressing JOYSEL. This corresponds to "pushing" the button and sending the related command.
Check box Link X	Enables or disables an option. It is always focusable and, when focused, can be activated by pressing JOYSEL. This corresponds to "check/uncheck" the control and means "enable/disable" the option.

11.2.1 Motor control application layer configuration (speed sensor)

The motor control application layer can be configured to use a position and speed sensor as a primary or auxiliary speed sensor.

A primary speed and position sensor is used by the FOC algorithm to drive the motor. It is mandatory to configure a primary speed sensor.

An auxiliary speed and position sensor may be used in parallel with the primary sensor for debugging purposes. It is not used by the FOC algorithm. It is not mandatory to configure an auxiliary speed sensor.

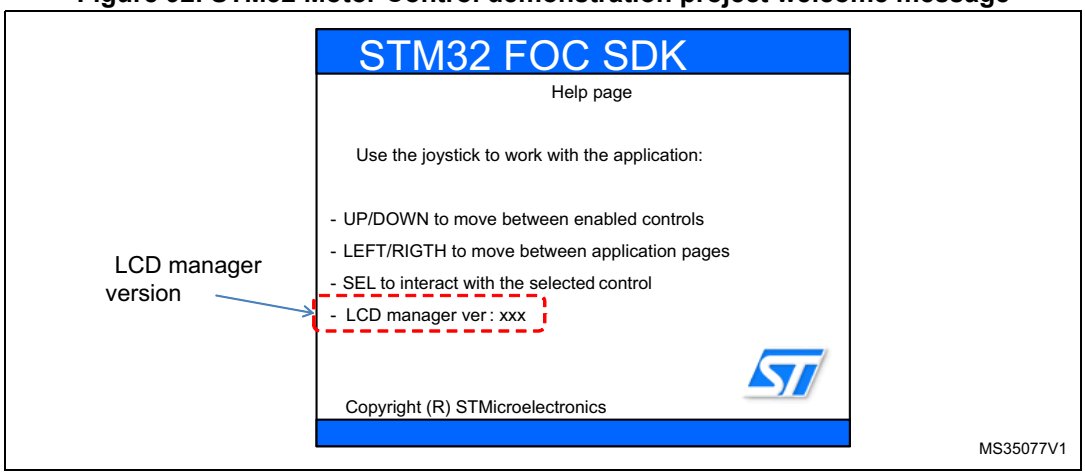
The following sensors are implemented in the MC library:

- Hall sensor
- Quadrature encoder
- State observer plus PLL
- State observer plus CORDIC

11.2.2 Welcome message

After the STM32 evaluation board is powered on or reset, a welcome message displays on the LCD screen to inform the user about the firmware code loaded and the version of the release. See *Figure 92*.

Figure 92. STM32 Motor Control demonstration project welcome message


STM32 FOC SDK
Help page
Use the joystick to work with the application:
- UP/DOWN to move between enabled controls
- LEFT/RIGTH to move between application pages
- SEL to interact with the selected control
- LCD manager ver : xxx
LCD manager version
Copyright (R) STMicroelectronics
MS35077V1

The page shows a brief help on the operation of the demonstration program. You can navigate to the next page by pressing the RIGHT joystick, or go back to the previous page by pressing the LEFT joystick.

Pressing the KEY button at any time starts or stops the motor. If you are using a dual motor control, pressing KEY stops both motors.

11.2.3 Configuration and debug page

Press the RIGHT joystick from the welcome page to enter the configuration and debug page.

To navigate between focusable controls on the page, press the UP/DOWN joystick.

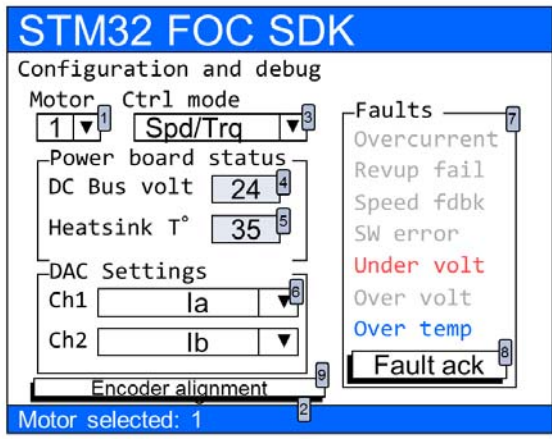
Use the configuration and debug page shown in *Figure 93* to:

- select the active motor drive (field 1 in *Figure 93*). This control is present only for dual motor control applications. This combo-box enables you to select the active motor drive. Once the active motor is selected, it is shown in the status bar present at the bottom of the screen (field 2 in *Figure 93*). Commands performed on, or feedback from

a control, are only relative to the active motor.

- select the control mode (field 3 in *Figure 93*). Two control modes are available: speed and torque. You can change the control mode from speed to torque and vice versa on-the-fly even if the motor is already running.

Figure 93. Configuration and debug page



MS33806V1

- read the DC bus voltage value (field 4 in *Figure 93*). This control is read-only.
- read the heat sink temperature value (field 5 in *Figure 93*). This control is read-only.
- select the variables to be put in output through DAC channels (field 6 in *Figure 93*). These controls are present only if the DAC option is enabled in the firmware. The list of variables also depends on firmware settings. *Table 21* and *Table 22* introduce the list of variables that can be present in these combo-boxes, depending on the configuration.

  Table 20 shows the conventions used for DAC outputs of Currents, Voltages, Electrical angles, Motor Speed and Observed BEMF.

Note: Table 20 assumes that the DAC voltage range is 0 to 3.3 volt.

Table 20. Definitions

Definition	Description
Currents quantity (Ia, Iq, …)	Current quantities are output to DAC as signed 16-bit numeric quantities converted in the range of DAC voltage range. – Zero current is at 1.65 volt of DAC output. – Maximum positive current (that runs from inverter to the motor) is at 3.3 volt of DAC output. – Maximum negative current (that runs from inverter to the motor) is at 0 volt of DAC output.
Voltage quantity (Valpha, Vq)	Voltage quantities are output to DAC as signed 16-bit numeric quantities converted in the range of DAC voltage range. – 0% of modulation index is at 1.65 volt of DAC output. – 100% of modulation index is at 0 and 3.3 volt of DAC output.
Electrical angle	This is expressed in digits converted to the DAC voltage range. – 180 electrical degrees are at 0 and 3.3 volt of DAC output. – 0 electrical degrees are at 1.65 volt of DAC output.

Table 20. Definitions

Definition	Description
Motor speed	This is proportional to the maximum application speed. – 0 speed is at 1.65 volt of DAC output. – Maximum positive application speed is at 3.3 volt of DAC output. – Maximum negative application speed is at 0 volt of DAC output.
Observer BEMF voltage	This is referenced to the maximum application speed and the voltage constant configured in the firmware. Values of BEMF present at the maximum application speed are at 0 and 3.3 volt of DAC output.

Table 21. List of DAC variables

Variable name	Description
Ia	Measured phase A motor current
Ib	Measured phase B motor current
Ialpha	Measured alpha component of motor phase's current expressed in alpha/beta reference.
Ibeta	Measured beta component of motor phase's current expressed in alpha/beta reference
Iq	Measured "q" component of motor phase's current expressed in q/d reference.
Id	Measured "d" component of motor phase's current expressed in q/d reference
Iq ref	Target "q" component of motor phase's current expressed in q/d reference
Id ref	Target "d" component of motor phase's current expressed in q/d reference
Vq	Forced "q" component of motor phase's voltage expressed in q/d reference
Vd	Forced "d" component of motor phase's voltage expressed in q/d reference
Valpha	Forced alpha component of motor phase's voltage expressed in alpha/beta reference.
Vbeta	Forced beta component of motor phase's voltage expressed in alpha/beta reference
Meas. El Angle	Measured motor electrical angle. This variable is present only if a "real" sensor (encoder, Hall) is configured as a primary or auxiliary speed sensor and it is relative to this sensor
Meas. Rotor Speed	Measured motor speed. This variable is present only if a "real" sensor (encoder, Hall) is configured as a primary or auxiliary speed sensor and it is relative to this sensor
Obs. El Angle	Observed motor electrical angle. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor
Obs. Rotor Speed	Observed motor speed. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor

Table 21. List of DAC variables (continued)

Variable name	Description
Obs. Ialpha	Observed alpha component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Ibeta	Observed beta component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor
Obs. B-emf alpha	Observed alpha component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. B-emf beta	Observed beta component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Exp. B-emf level	The expected Bemf squared level.
Obs. B-emf level	The observed Bemf squared level.
User 1	User defined DAC variable. *Section 13.9* describes how to configure user defined DAC variables.
User 2	User defined DAC variable. *Section 13.9* describes how to configure user defined DAC variables.

Observed variables (Obs.) in *Table 21* refer to a configuration that uses only one sensorless speed sensor configured as a primary or auxiliary sensor and refers to that state observer sensor. When the firmware is configured to use two sensorless speed sensors, state observer plus PLL and state observer plus CORDIC as a primary and auxiliary speed sensor, the DAC variables related to each state observer sensor are indicated in *Table 22*.

Table 22. DAC variables related to each state observer sensor

Variable name	Description
Obs. El Ang. (PLL)	Observed motor electrical angle. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Ialpha (PLL)	Observed alpha component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Rot. Spd (PLL)	Observed motor speed. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Ibeta (PLL)	Observed beta component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Bemf a. (PLL)	Observed alpha component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.

Table 22. DAC variables related to each state observer sensor

Variable name	Description
Obs. Bemf b. (PLL)	Observed beta component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer plus PLL" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. El Ang. (CR)	Observed motor electrical angle. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Rot. Spd (CR)	Observed motor speed. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Ialpha (CR)	Observed alpha component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Ibeta (CR)	Observed beta component of motor phase's current expressed in alpha/beta reference. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Bemf a. (CR)	Observed alpha component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.
Obs. Bemf b. (CR)	Observed beta component of motor BEMF expressed in alpha/beta reference. This variable is present only if a "state observer plus CORDIC" sensor is configured as a primary or auxiliary speed sensor and it is relative to this sensor.

Table 22 lists the DAC variables related to each state observer sensor when two state observer speed sensors are selected.

- It is possible to read the list of fault causes (field 7 in *Figure 93*) if fault conditions have occurred, or if they are still present. The list of possible faults is summarized in *Table 23* and is represented by the list of labels in the LCD screen (field 7 in *Figure 93*). If a fault condition occurred and is over, the relative label is displayed in blue. If a fault condition is still present, the relative label is displayed in red. It is gray if there is no error.
- To acknowledge the fault condition, press the "Fault ack" button (field 8 in *Figure 93*). If a fault condition occurs, the motor is stopped and it is no longer possible to navigate in the other pages. In this condition, it is not possible to restart the motor until the fault condition is over and the occurred faults have been acknowledged by the user pushing the "Fault ack" button. If a fault condition is running, the "Fault ack" button is disabled.

Table 23. Fault conditions list

Fault	Description
Overcurrent	This fault occurs when the microcontroller break input signal is activated. It is usually used to indicate hardware over current condition.
Revup fail	This fault occurs when the programmed rev-up sequence ends without validating the speed sensor information. The rev-up sequence is performed only when the state observer is configured as the primary speed sensor.
Speed fdbk	This fault occurs only in RUN state when the sensor no longer meets the conditions of reliability.
SW error	This fault occurs when the software detects a general fault condition. In the present implementation, the software error is raised when the FOC frequency is too high to allow the FOC execution.
Under volt	This fault occurs when the DC bus voltage is below the configured threshold.
Over volt	This fault occurs when the DC bus voltage is above the configured threshold. If the dissipative brake resistor management is enabled, this fault is not raised.
Over temp	This fault occurs when the heat sink temperature is above the configured threshold.

- Execute the encoder initialization. If the firmware is configured to use the encoder as a primary speed sensor or an auxiliary speed sensor, the "encoder alignment" button is also present. In this case, the alignment of the encoder is required only once after each reset of the microcontroller.

11.2.4 Dual control panel page

This page is present only if the firmware is configured for a dual motor drive.

To enter the dual control page, press the RIGHT joystick from configuration and debug page.

It is possible to navigate between focusable controls present in the page by pressing the UP/DOWN joystick.

The dual control panel page shown *Figure 94* is used to send commands and get feedback from both motors. It is divided into three groups:

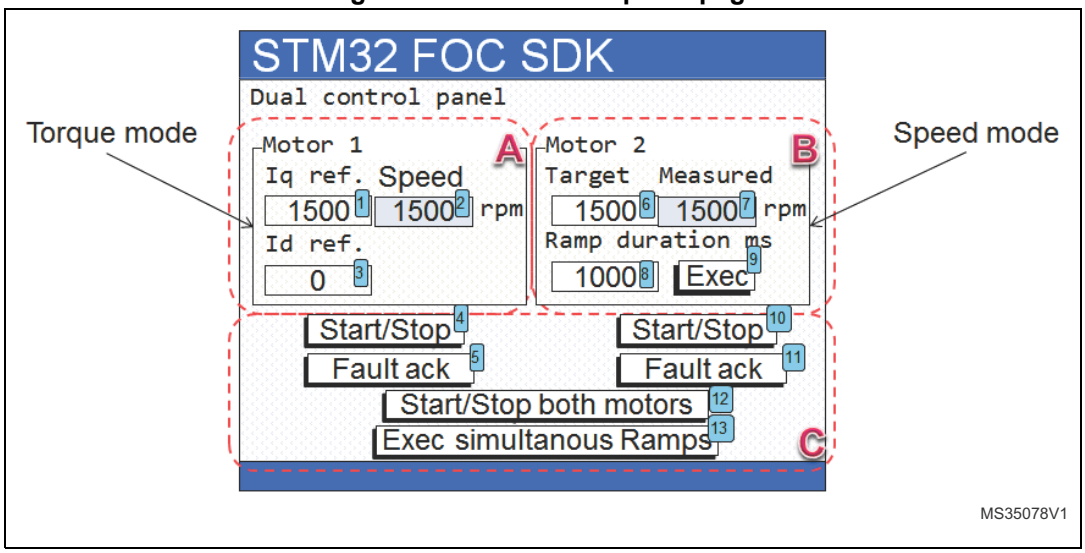
- Group A and group B depend on speed/torque settings. The group content is updated on-the-fly when the control mode (torque/speed) is changed in the configuration and debug page. The control present in group A is related to the first motor. The control present in group B relates to the second motor.
- Group C does not depend on speed/torque settings. The control present in this group is related to both motors.

Figure 94 shows an example in which the first motor is set in torque mode and the second motor is set in speed mode.

The controls present in this page are used as follows:

- To set the I_q reference (field 1 in *Figure 94*). This is related to motor 1 and is only present if motor 1 is set in torque mode. I_q reference is expressed in s16A. In this page, the current references are always expressed as Cartesian coordinates (I_q,I_d).

Figure 94. Dual control panel page



- To set the I_d reference (field 3 in *Figure 94*). This is related to motor 1. This control is only present if motor 1 is set in torque mode. I_d reference is expressed in s16A. In this page, the current references are always expressed as Cartesian coordinates (I_q,I_d).

Note: To convert current expressed in Amps to current expressed in digit, it is possible to use the following formula:

*Current(s16A) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro.*

- Set the final motor speed of a speed ramp (field 6 in *Figure 94*). This is related to motor 2. This control is only present if motor 2 is set in speed mode. Motor speed is expressed in RPM. The value set in this control is not automatically sent to the motor control related object but it is used to perform a speed ramp execution. See the Exec button description (field 9 in *Figure 94*).
- Set the duration of a speed ramp (field 8 in *Figure 94*). This is related to motor 2. This control is only present if motor 2 is set in speed mode. The duration is expressed in milliseconds. The value set in this control is not automatically sent to the motor control related object, but it is used to perform a speed ramp execution. See the Exec button description (field 9 in *Figure 94*). It is possible to set a duration value of 0 to program a ramp with an instantaneous change in the speed reference from the current speed to the final motor speed (field 6 in *Figure 94*).
- Execute a speed ramp by pushing the "Exec" button (field 9 in *Figure 94*). This is related to motor 2. This control is only present if motor 2 is set in speed mode. The Exec speed ramp command is sent to the motor control related object together with the final motor speed and duration currently selected (field 6 and 8 in *Figure 94*). The Exec speed ramp command performs a speed ramp from the current speed to the final motor speed in a time defined by duration. The command is buffered and takes effect only when the motor is in RUN state.
- To read the motor speed (field 2 and 7 in *Figure 94* respectively for motor 1 and motor 2). The motor speed is expressed in RPM. This control is read-only.
- Send a start/stop command (field 4 for motor 1, field 10 for motor 2 in *Figure 94*). This is performed by pushing the start/stop button. A start/stop command means: start the motor if it is stopped, or stop the motor if it is running. If the drive is configured in speed mode when the motor starts, a speed ramp with the latest values of final motor speed

and duration is performed. If a fault condition occurs at any time, the motor is stopped (if running) and the start/stop button is disabled.

- When a fault condition is over, the "Fault ack" button (field 5 for motor 1, field 11 for motor 2 in *Figure 94*) is enabled. Pushing this button acknowledges the fault conditions that have occurred. After the fault is acknowledged, the start/stop button becomes available again. When a fault occurs and before it is acknowledged, it is only possible to navigate in the Dual control panel page and the Configuration and debug page.
- To start or stop both motors simultaneously, push the "start/stop both motors" button (field 12 in *Figure 94*). This button is enabled only when the motors are both in Idle state or both in RUN state. If any of the motors are configured in speed mode when they start, a speed ramp with the last values of final motor speed and duration is performed. It is possible to stop both motors at any time by pushing the KEY button.
- To execute simultaneous speed ramps on both motors, push the Exec simultaneous ramps button (field 13 in *Figure 94*). This button is disabled when at least one of the two motors is configured in torque mode. The Exec speed ramp command is sent to both motor control objects together with related final motor speed and duration currently selected. The Exec speed ramp command performs a speed ramp from the current speed to the final motor speed in a time defined by duration for each motor. The commands are buffered and take effect only when the related motor is in RUN state.

11.2.5 Speed controller page

This page is only present if the control mode set in ctrl mode (field 3 in *Figure 93*) is the speed mode.

To enter the speed controller page, press the RIGHT joystick from the configuration and debug page (or from the dual control panel page, if the firmware is configured in dual motor drive).

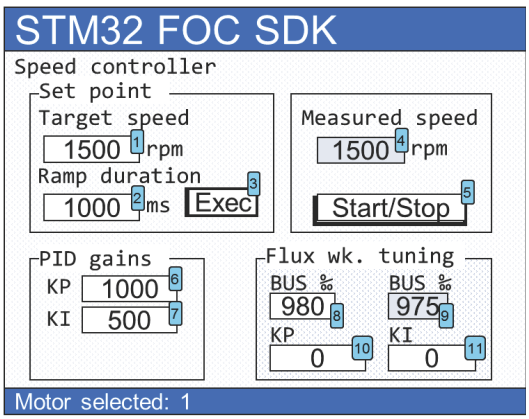
It is possible to navigate between focusable controls present in the page by pressing the UP/DOWN joystick.

The speed controller page shown in *Figure 95* is used to send commands and get a feedback related to the speed controller from the active motor. There are four groups of control in this page, listed in the table below.

Table 24. Control groups

Control group	Description
Set point	Used to configure and execute a speed ramp.
PID gains	Used to change the speed controller gains in real-time.
Flux wk. tuning	Used to tune the flux weakening related variables.
Measured speed with start/stop button	Composed of two controls that are also present in the current controller page and in the sensorless tuning page; this provides a fast access to the measured speed and to the motor start/stop function.

Figure 95. Speed controller page



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If the firmware is configured as a dual motor drive, it is possible to know which is the active motor by reading the label at the bottom of the page. To change the active motor, change the motor field in the configuration and debug page (field 1, *Figure 95*).

Table 25 lists the actions that can be performed using this page.

Table 25. Speed controller page controls

Control	Description
Target speed (field 1 in *Figure 95*)	This sets the final motor speed of a speed ramp for the active motor. The motor speed is expressed in RPM. The value set in this control is not automatically sent to the motor control related object, but it is used to perform a speed ramp execution. See the Exec button description (field 3 in *Figure 95*).
Ramp duration (field 2 in *Figure 95*)	This sets the duration of a speed ramp for the active motor. The duration is expressed in milliseconds. The value set in this control is not automatically sent to the motor control related object but it is used to perform a speed ramp execution. See the description of the "exec" button (field 3 in *Figure 95*). It is possible to set a duration value of 0 to program a ramp with an instantaneous change in the speed reference from the current speed to the final motor speed (field 1 in *Figure 95*).
Exec button (field 3 in *Figure 95*)	This executes a speed ramp for the active motor. The execute speed ramp command is sent to the motor control related object together with the final motor speed and duration presently selected (field 1 and 2 in *Figure 95*). The execute speed ramp command performs a speed ramp from the current speed to the final motor speed in a time defined by duration. The command is buffered and takes effect only when the motor becomes in RUN state.
Measured speed (field 4 in *Figure 95*)	This reads the motor speed for the active motor. The motor speed is expressed in RPM and is a read-only control.
Start/Stop button (field 5 in *Figure 95*)	This sends a start/stop command for the active motor. A start/stop command starts the motor if it is stopped, or stops a running motor. Used with a motor start, a speed ramp with the last values of the final motor speed and duration is performed. If a fault condition occurs at any time, the motor is stopped (if running) and the configuration and debug page displays.

Table 25. Speed controller page controls (continued)

Control	Description
Speed PID gain KP (field 6 in *Figure 95*)	This sets the proportional coefficient of the speed controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the speed controller.
Speed PID gain KI (field 7 in *Figure 95*)	This sets the integral coefficient of the speed controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the speed controller.
Bus‰ (field 8 in *Figure 95*)	This sets the maximum percentage quantity of DC bus that can be utilized for a flux weakening operation for the active motor. This control is present only if the flux weakening feature is enabled in the firmware. This value should be a trade-off between bus voltage exploitation (a higher bus means that a greater speed can be achieved) and control margin (the remaining bus voltage from that value to 100% is available for the current regulation used by current regulators. If it is too low, the control is no longer possible). The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of flux weakening controller. The value is expressed in permillage (‰) of DC bus voltage.
Bus‰ (field 9 in *Figure 95*)	This reads the quantity of DC bus voltage percentage presently used for the active motor and is a read-only control. This control is present only if the flux weakening feature is enabled in the firmware. The value is actually expressed in permillage (‰) of DC bus voltage.
Flux wk PI gain KP (field 10 in *Figure 95*)	the proportional coefficient of the flux weakening controller for the active motor. This control is only present if the flux weakening feature is enabled in the firmware. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the flux weakening controller.
Flux wk PI gain KI (field 11 in *Figure 95*)	Sets the integral coefficient of the flux weakening controller for the active motor. This control is only present if the flux weakening feature is enabled in the firmware. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the flux weakening controller.

11.2.6 Current controller page

To enter the current controller page, press the RIGHT joystick from the speed controller page (or from one of the above described pages if the speed controller page is not visible).

It is possible to navigate between focusable controls present in the page, pressing the UP/DOWN joystick.

The current controller page shown in *Figure 96* is used to send commands and get a feedback related to current controllers, from the active motor. There are five control groups in this page, listed in the table below.

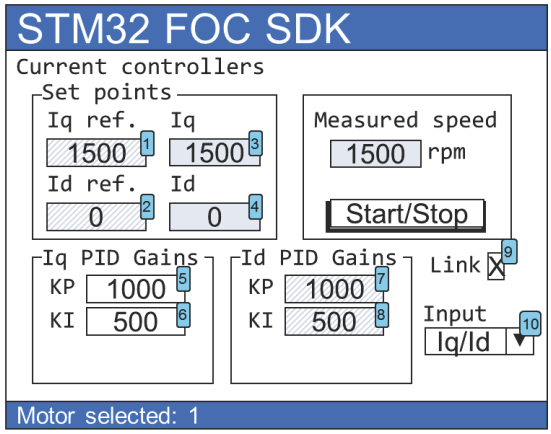
Table 26. Control groups

Control group	Description
Set point	Used to set the current references and read measured currents
Iq PID gains	Used to change in real time the speed controller gains
Id PID gains	

Table 26. Control groups

Control group	Description
Measured speed with start/stop button	Composed of two controls that are also present in the current controller page and in the sensorless tuning page; this provides a fast access to the measured speed and to the motor start/stop function
Option selection	Selects options

Figure 96. Current controller page



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If the firmware is configured as a dual motor drive, it is possible to know which is the active motor reading the label at the bottom of the page. To change the active motor, the motor field in the configuration and debug page has to be changed (field 1 in *Figure 96*).

Table 27 lists the actions that can be performed using this page.

Table 27. Current controller page controls

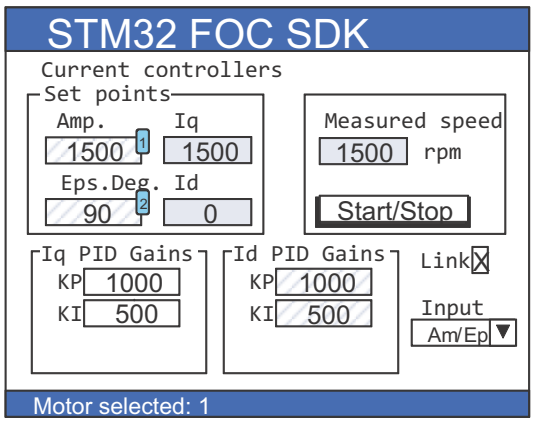
Control	Description
I_q reference (field 1 in *Figure 96*)	To set and read the I_q reference for the active motor. This control is read-only if the active motor is set in speed mode, otherwise it can be modified. The I_q reference is expressed in s16A. To convert current expressed in Amps to current expressed in digits, use the formula: Current(s16A) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro
I_d reference (field 2 in *Figure 96*)	To set and read the I_d reference for the active motor. This control is usually read-only if the active motor is set in speed mode, otherwise it can be modified. The I_d reference is expressed in digits. It is also possible to configure the firmware to have an I_d reference editable even in speed mode. To convert current expressed in Amps to current expressed in s16A, it is possible to use the formula: Current(s16A) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro
Measured I_q (field 3 in *Figure 96*)	To read the measured I_q for the active motor. Measured I_q is expressed in s16A and is a read-only control.
Iq PI(D) gain, KP (field 5 in *Figure 96*)	To set the proportional coefficient of the I_q current controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller.

Table 27. Current controller page controls (continued)

Control	Description
Iq PI(D) gain, KI (field 6 in *Figure 96*)	To set the integral coefficient of the I_q current controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller.
Id PI(D) gain, KP (field 7 in *Figure 96*)	To set the proportional coefficient of the I_d current controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller. This control is only read if the link check-box is checked.
Id PI(D) gain, KI (field 8 in *Figure 96*)	To set the integral coefficient of the I_d current controller for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller. This control is only read if the link check-box is checked.

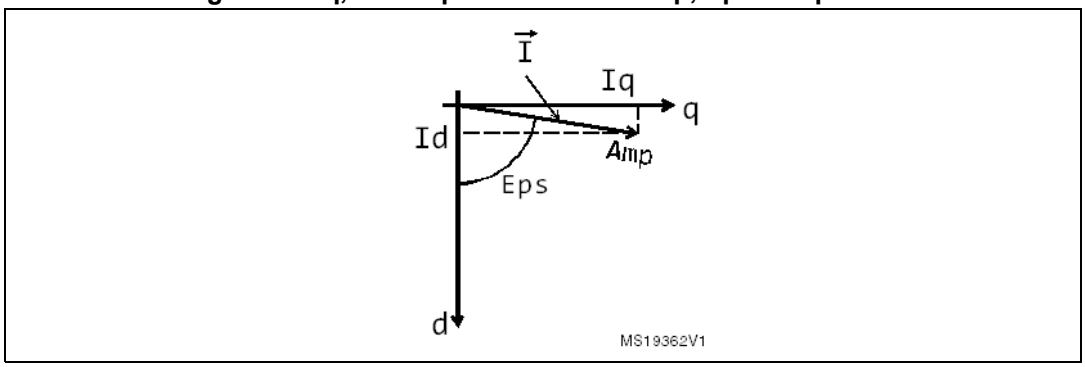
Enabling or disabling the link between I_q and I_d controllers KP and KI gains is performed by checking or unchecking the link check-box (field 9 in *Figure 96*). It is possible to change the current reference variables from Cartesian coordinates (Iq/Id) to polar coordinates (Amp, Eps *Figure 97*) using the input combo-box (field 10 in *Figure 96*). If polar coordinates are selected, the current controller page is modified as in *Figure 97*.

Figure 97. Current controller page with polar coordinates



- The Amp field (field 1 in *Figure 97*) is used to set and read the current reference amplitude for the active motor. This control is read-only if the active motor is set in speed mode, otherwise it is editable. Amplitude reference is expressed in digits.
- The Eps field (field 2 in *Figure 97*) is used to set and read the current reference phase for the active motor. This control is read-only if the active motor is set in speed mode, otherwise it is editable. The phase is expressed in degrees.

Figure 98. Iq, Id component versus Amp, Eps component



11.2.7 Sensorless tuning STO & PLL page

This page is present only if the firmware is configured to use a state observer (STO) plus a PLL sensor set as a primary or auxiliary speed and position sensor. If the state observer sensor is set as an auxiliary speed and position sensor, the (AUX) label will be shown near the page title (See field 9 in *Figure 99*).

To enter the sensorless tuning page, press the RIGHT joystick from the current controller page.

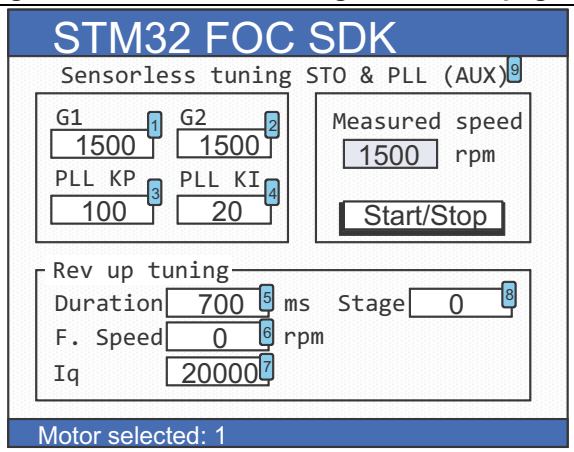
It is possible to navigate between focusable controls present in the page by pressing the UP/DOWN joystick.

The sensorless tuning page shown in *Figure 99* is used to send commands and get a feedback related to a state observer plus a PLL object from the active motor. There are three groups of control in this page.

Table 28. Control groups

Control group	Description
State observer tuning	Used to configure the parameters of the state observer object in real-time
Rev up tuning gains	Used to change the start up related parameters in real-time. This group is only present if the state observer plus PLL sensor is selected as the primary speed and position sensor.
Measured speed with start/stop button	Composed of two controls that are also present in the current controller page and in the sensorless tuning page; this provides a fast access to the measured speed and to the motor start/stop function

Figure 99. Sensorless tuning STO & PLL page



If the firmware is configured as a dual motor drive, it is possible to know which is the active motor by reading the label at the bottom of the page. To change the active motor, change the motor field in the configuration and debug page.

Table 29 lists the actions that can be performed using this page.

Table 29. Sensorless tuning STO & PLL page controls

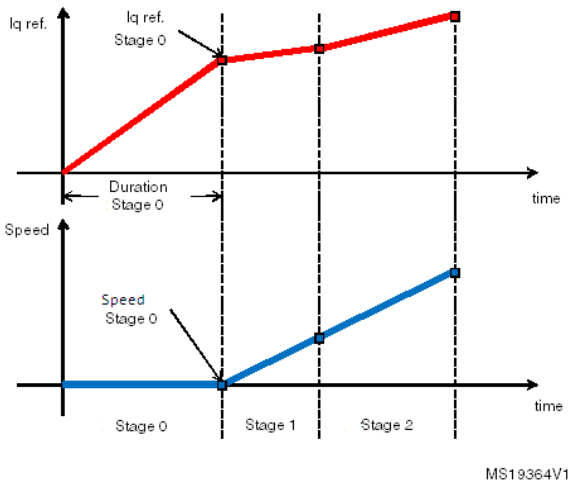
Control	Description
G1 (field 1 in *Figure 99*)	To modify the G1 gain parameter in real-time. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the state observer object. This value is proportional to the K1 observer gain and is equal to C2 STO object parameter (See *STM32 FOC PMSM FW library developer Help file.chm*).
G2 (field 2 in *Figure 99*)	To modify the G2 gain parameter in real-time. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the state observer object. This value is proportional to the K2 observer gain and is equal to C4 STO object parameter (See *STM32 FOC PMSM FW library developer Help file.chm*).
PLL KP (field 3 in *Figure 99*)	To set the proportional coefficient of the PLL for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller. This control is only present if the state observer + PLL object is set as the primary or auxiliary speed and position sensor, and if the PLL tuning option is enabled in the firmware.
PLL KI (field 4 in *Figure 99*)	To set the integral coefficient of the PLL for the active motor. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the current controller. This control is only present if the state observer + PLL object is set as the primary or auxiliary speed and position sensor, and if the PLL tuning option is enabled in the firmware.
Duration (field 5 in *Figure 99*)	To set the duration of the active rev-up stage for the active motor. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the tuning of the rev-up sequence. The duration is expressed in milliseconds.

Table 29. Sensorless tuning STO & PLL page controls (continued)

Control	Description
F. Speed (field 6 in *Figure 99*)	To set the final mechanical speed for the active motor and active rev-up controller stage. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the run-time tuning of rev-up sequence. The final mechanical speed is expressed in RPM.
I_q (field 7 in *Figure 99*)	To set the final torque reference for the active motor and active rev-up controller stage. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the tuning of the rev-up sequence. The final torque reference is expressed in I_d current and becomes active on next motor start-up. To convert current expressed in Amps to current expressed in digits, use the formula: Current(s16A) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro.
Stage (Field 8 in *Figure 99*)	To set the active rev-up stage that receives the Duration, F. Speed and Final torque reference (Iq) new values set in Fields 5, 6 and 7.

The rev-up sequence consists of five stages. *Figure 100* shows an example of a rev-up sequence. It is possible to tune each stage in run-time using rows 5-8 of *Table 29*.

Figure 100. Example of rev-up sequence



11.2.8 Sensorless tuning STO & CORDIC page

This page is only present if the firmware is configured to use a state observer plus CORDIC sensor set as a primary or auxiliary speed and position sensor. If the state observer sensor is set as an auxiliary speed and position sensor, the (AUX) label will be shown near the page title (See field 7 in *Figure 101*).

To enter the sensorless tuning page, press the RIGHT joystick from the current controller page.

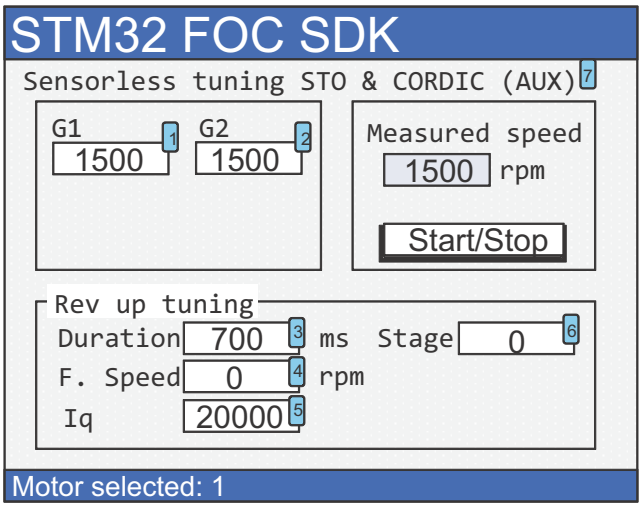
It is possible to navigate between focusable controls present in the page by pressing the UP/DOWN joystick.

The sensorless tuning page shown in *Figure 101* is used to send commands and get feedbacks, related to the state observer plus CORDIC object, from the active motor. There are three groups of controls in this page.

Table 30. Control groups

Control group	Description
State observer tuning	Used to configure the parameters of the state observer object in real-time
Rev up tuning gains	Used to change the start-up related parameters in real-time. This group is only present if the state observer plus CORDIC sensor is selected as the primary speed and position sensor.
Measured speed with start/stop button	Composed of two controls that are also present in the current controller page and in the sensorless tuning page; this provides a fast access to the measured speed and to the motor start/stop function

Figure 101. Sensorless tuning STO & CORDIC page



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If the firmware is configured as a dual motor drive, it is possible to know which is the active motor by reading the label at the bottom of the page. To change the active motor, change the motor field in the configuration and debug page.

Table 31 lists the actions that can be performed using this page.

Table 31. Sensorless tuning STO & PLL page controls

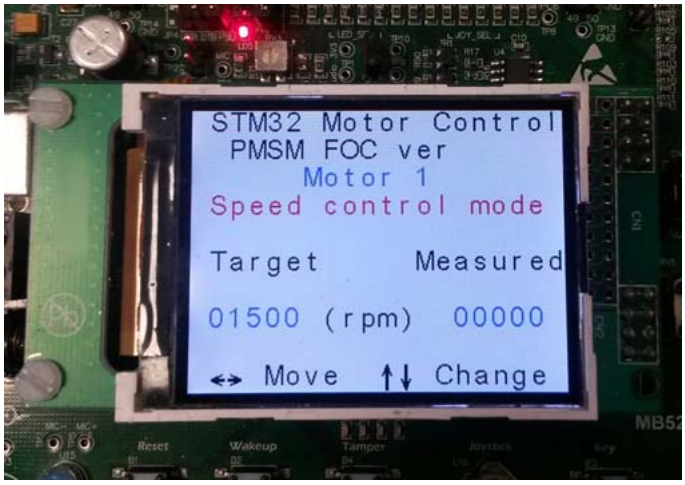
Control	Description
G1 (field 1 in *Figure 101*)	To modify the G1 gain parameter in real-time. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the state observer object. This value is proportional to the K1 observer gain and is equal to C2 STO object parameter (See doxygen.chm).
G2 (field 2 in *Figure 101*)	To modify the G2 gain parameter in real-time. The value set in this control is automatically sent to the motor control related object, allowing the run-time tuning of the state observer object. This value is proportional to the K2 observer gain and is equal to C4 STO object parameter (See doxygen.chm).
Duration (field 3 in *Figure 101*)	To set the duration of the active rev-up stage for the active motor. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the tuning of the rev-up sequence. The duration is expressed in milliseconds.
F. Speed (field 4 in *Figure 101*)	To set the final mechanical speed for the active motor and active rev-up controller stage. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the run-time tuning of the rev-up sequence. The final mechanical speed is expressed in RPM.
I_q (field 5 in *Figure 101*)	To set the final torque reference for the active motor and active rev-up controller stage. The value set in this control is automatically sent to the motor control related object and becomes active on next motor start-up, allowing the tuning of the rev-up sequence. The final torque reference is expressed in I_d current and becomes active on next motor start-up. To convert current expressed in Amps to current expressed in digits, use the formula: Current(s16A) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro.
Stage (Field 8 in *Figure 101*)	To set the active rev-up stage that receives the Duration, F. Speed and Final torque reference (Iq) new values set in Fields 5, 6 and 7.

It is possible to set the active rev-up stage (field 6 in *Figure 101*). *Figure 100* shows an example of a rev-up sequence.

12 Light LCD user interface

The STM32 motor control library includes a simplified version of demonstration program that enables you to display drive variables, customize the application by changing parameters, and enable and disable options in real time. It is shown in *Figure 102*.

Figure 102. Light LCD User interface

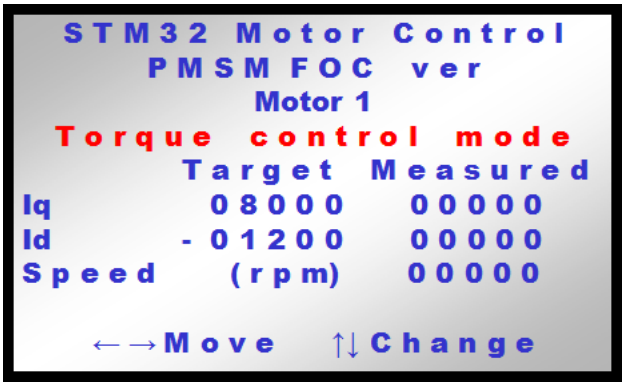


12.1 Torque control mode

Figure 103, *Figure 104* and *Figure 105* show a few LCD menus for setting control parameters when in Torque Control mode. The parameter highlighted, in red color, is the one that can be set and its value can be modified by acting on the joystick key.

Moving the joystick up/down, selects the active control mode (in the example shown in *Figure 103*, it is Torque control).

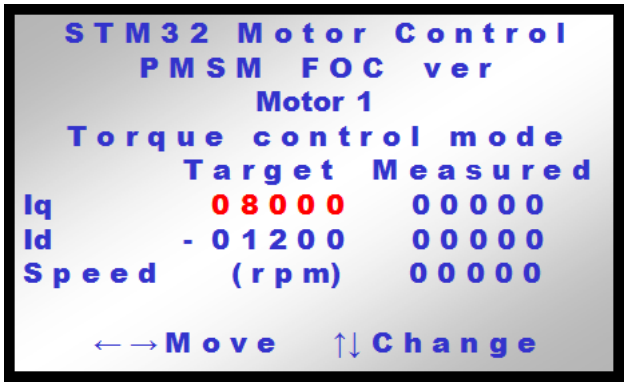
Figure 103. LCD screen for Torque control settings



From the previous screen (*Figure 103*), if the joystick is moved to the right, the Target I_q current component becomes highlighted (in red). This parameter can now be modified by moving the joystick up/down. Once the motor Start command has been issued, Target I_q can

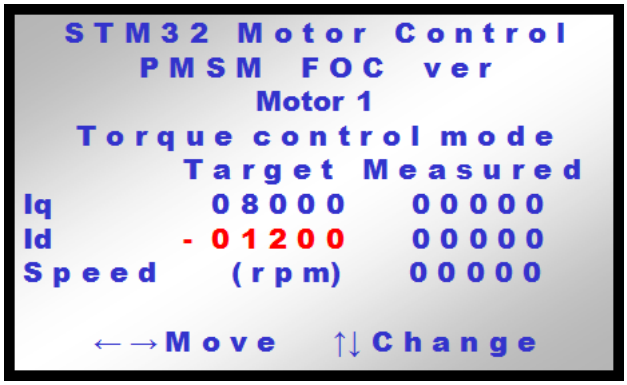
be changed in runtime while the measured I_q current component is shown in the ***Measured*** field.

Figure 104. LCD screen for Target Iq settings



From the previous screen (*Figure 104*), if the joystick is moved to the right, the Target I_d current component becomes highlighted (in red). This parameter can now be modified by moving the joystick up/down. Once the motor Start command has been issued, the Target I_d can be changed in runtime while the measured Id current component is shown in the Measured field.

Figure 105. LCD screen for Target Id settings

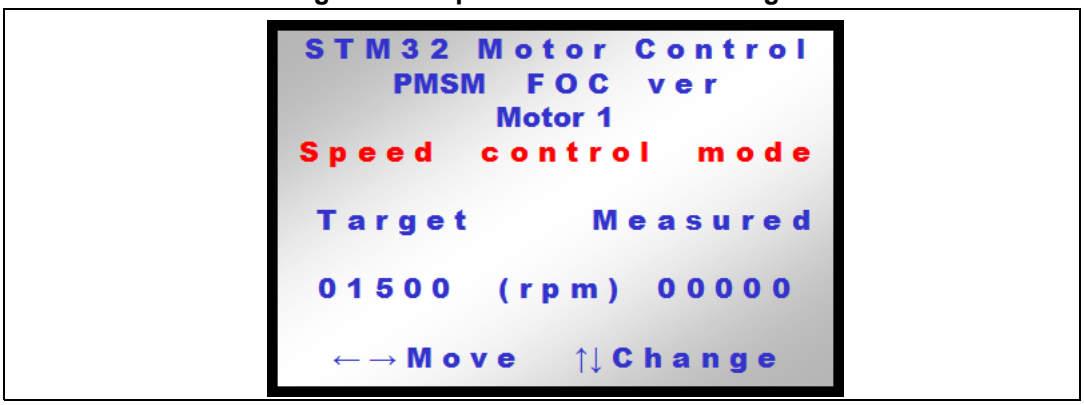


12.2 Speed control mode

Figure 106 and *Figure 107* show two LCD menus used to set control parameters when in Speed control mode. The parameter highlighted in red color can be set and its value can be modified by acting on the joystick key.

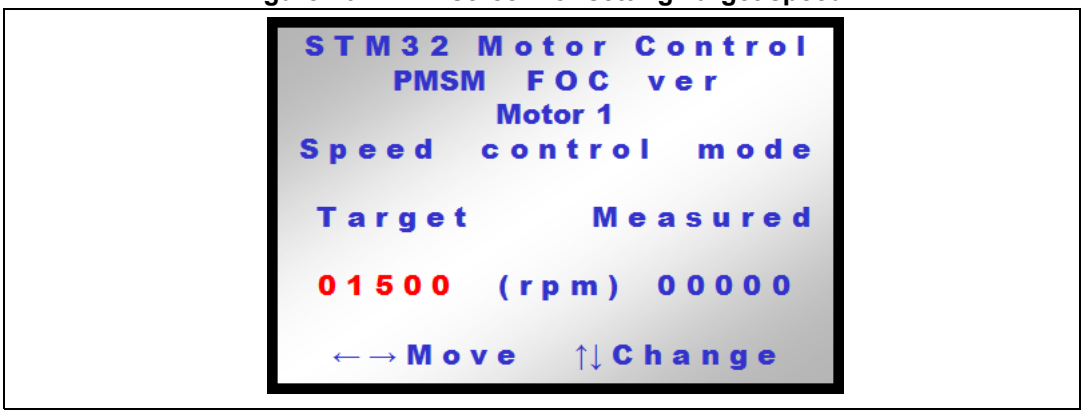
From the menu screen shown in *Figure 106*, it is possible to switch from Torque control to Speed control operations (and vice versa) by moving the joystick up/down.

Figure 106. Speed control main settings



From the menu screen shown in *Figure 106*, moving the joystick to the right selects the Target speed (parameter highlighted in red). Once selected, the parameter can be incremented/decremented by moving the joystick up/down. The motor can then be started simply by pressing the joystick. When the motor is on, the target speed can still be modified.

Figure 107. LCD screen for setting Target speed



Like in the torque control mode, the motor is started/stopped by pressing the joystick or the KEY button.

Since in speed control mode, the torque and flux parameters (Target Iq and Target Id) are the outputs of the Torque and flux controller, they cannot be set directly. The PID regulators can however be real-time tuned as explained below.

12.3 Currents and speed regulator tuning

Next figures show the two LCD menus allowing the real-time tuning of the proportional, integral gains:

Figure 108 shows the screen used to select either of the torque PID coefficients whereas *Figure 109* shows the screen used to select either of the flux PID coefficients. From both screen, either of the P, I coefficient can be selected (highlighted in red) by moving the joystick to the right/left. Then, each value can be changed (incremented or decremented) by pressing the joystick up/down.

Figure 108. LCD screen for setting the P term of torque PID

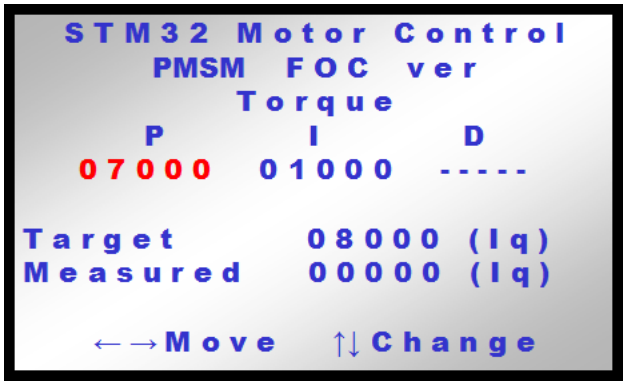
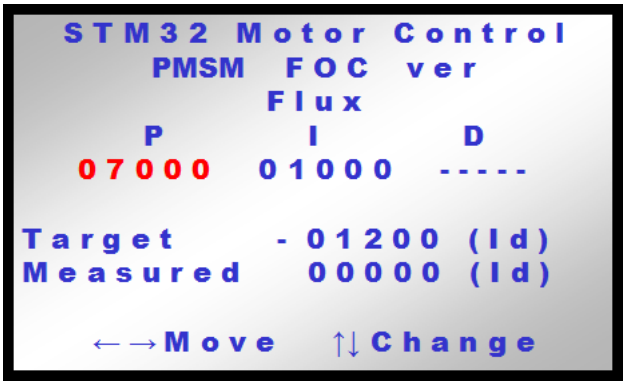
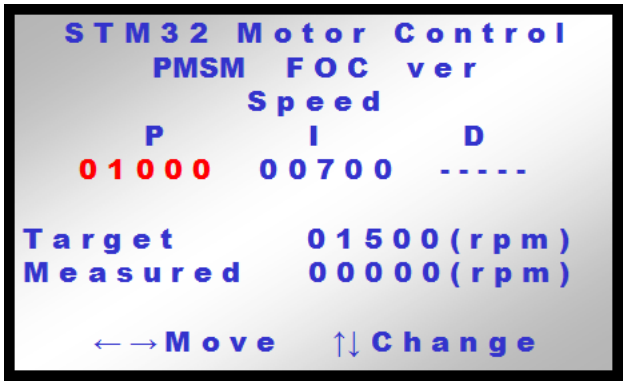


Figure 109. LCD screen for setting the P term of the speed PID



Moreover, to achieve speed regulation in speed control mode, a PI is also implemented. The tuning of its related gains can be done in real time by means of the dedicated LCD menu:

Figure 110. LCD screen for setting the P term of the speed PID



Like for the previous menus, either of the P or I coefficients can be selected (highlighted in red) by moving the joystick to the right/left. The desired values can then be changed (incremented or decremented) by pressing the joystick up/down.

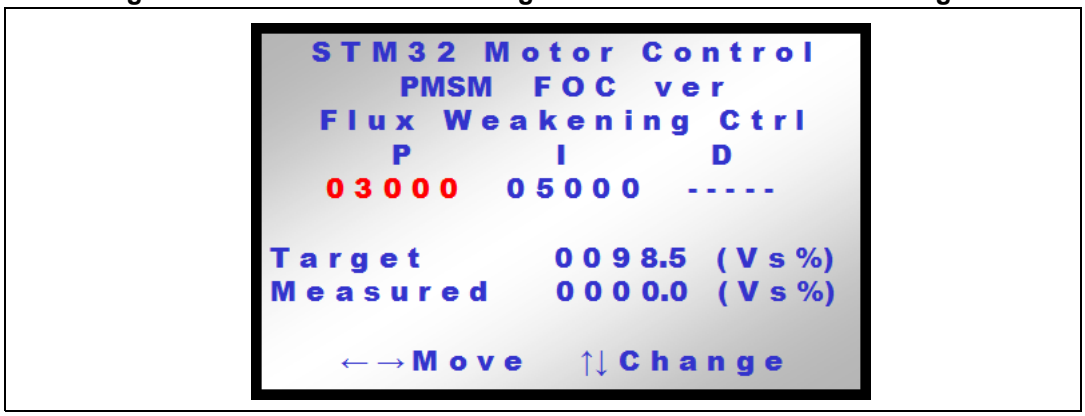
12.4 Flux-weakening PI controller tuning

This menu is available if the flux-weakening functionality has been enabled in the ST MC Workbench project.

It is used to real-time tune the proportional and integral gains of the PI regulator used inside the flux-weakening block.

Either the P coefficient, I coefficient or the target stator voltage Vs can be selected (highlighted in red) by moving the joystick to the right/left. The desired values can then be changed (incremented or decremented) by pressing the joystick up/down. *Figure 111* shows the screen used for the tuning operation.

Figure 111. LCD screen for setting the P term of the flux-weakening PI

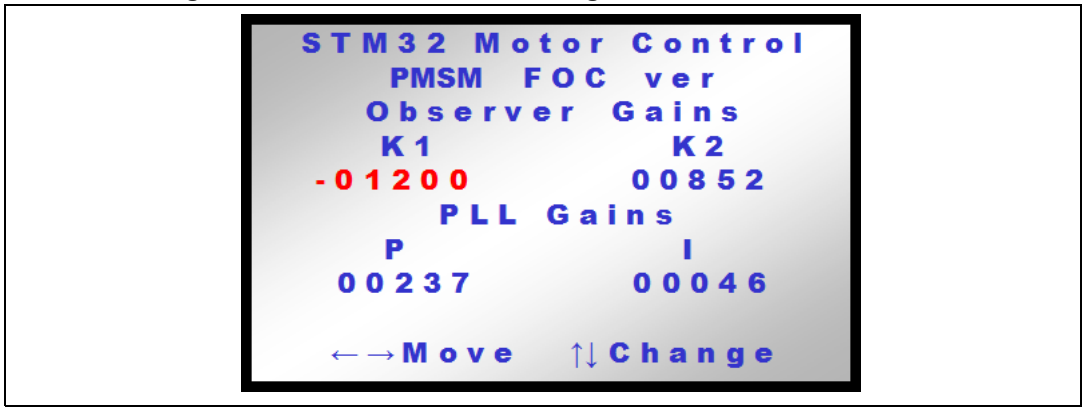


The target and measured stator voltages are shown in the lower part of the screen as a percentage of the maximum available phase voltage.

12.5 Observer and PLL gain tuning

When state observer is set as main or auxiliary speed and position sensor in the ST MC Workbench project, a dedicated menu is shown on the LCD to tune the observer and PLL gains (*Figure 112*).

Figure 112. LCD screen for setting the P term of the flux PID



When the menu in *Figure 112* is displayed, the joystick can be moved to the right/left to navigate between the different gains. Pressing the joystick up/down will increment/decrement the gain highlighted in red color.

This menu is used to change both the observer and the PLL gains in real time. This feature is particularly useful when used in conjunction with the DAC functionality and with a firmware configuration handling either Hall effect sensors or an encoder. In this way, it is possible to modify the observer and PLL gains by looking for example at both the observed and measured rotor electrical angle and by adjusting the gains so as to cancel any error between the two waveforms.

12.6 DAC functionality

When enabled in the ST MC Workbench project, the DAC functionality is a powerful debug tool which allows the simultaneous tracing of up to two software variables selectable in real time using a dedicated menu.

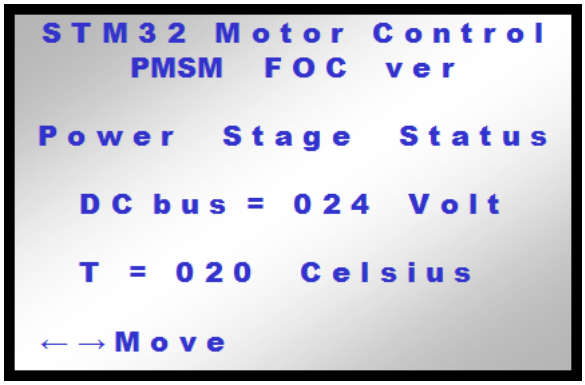
Figure 113. LCD screen for setting the P term of the flux PID

When the menu in *Figure 113* is displayed, the joystick can be moved to the right/left to select the desired DAC channel. To change the software variable in output, move the joystick up/down (the list of the available variables depends on the selected firmware configuration). For all other menus, pressing the joystick or the Key button will cause the motor to start/stop.

12.7 Power stage feedbacks

A dedicated menu was designed to show the value in volts of the DC bus voltage and the temperature of the heat sink.

Figure 114. Power stage status



12.8 Fault messages

This section provides a description of all the possible fault messages that can be detected when using the software library. *Figure 115* shows a typical error message as displayed on the LCD.

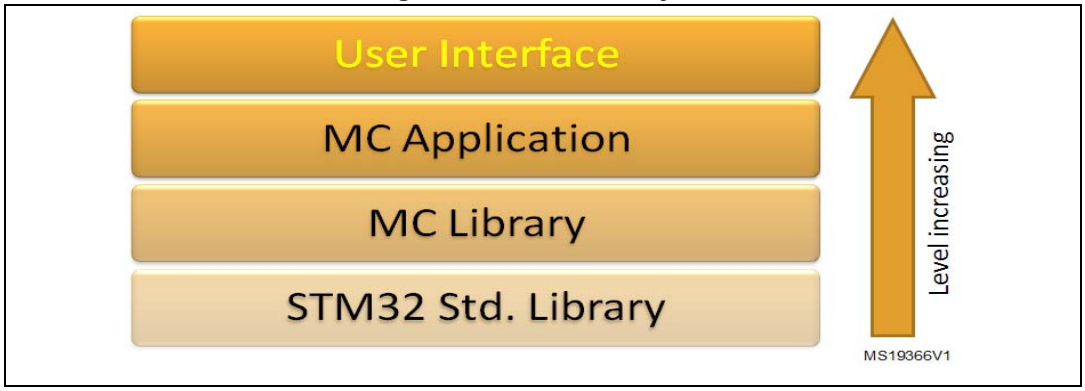
Figure 115. Error message shown in the event of an undervoltage fault

The message "*Press 'Key' to return to menu*" is visible only if the source of the fault has disappeared. In this case, pressing the 'Key' button causes the main state machine to switch from the Fault occurred state to the Idle state.

13 User Interface class overview

The STM32 FOC motor control firmware is arranged in software layers (*Figure 116*). Each level can include the interface of the next level, with the exception that the STM32 Std. Library can be included in every level.

Figure 116. Software layers



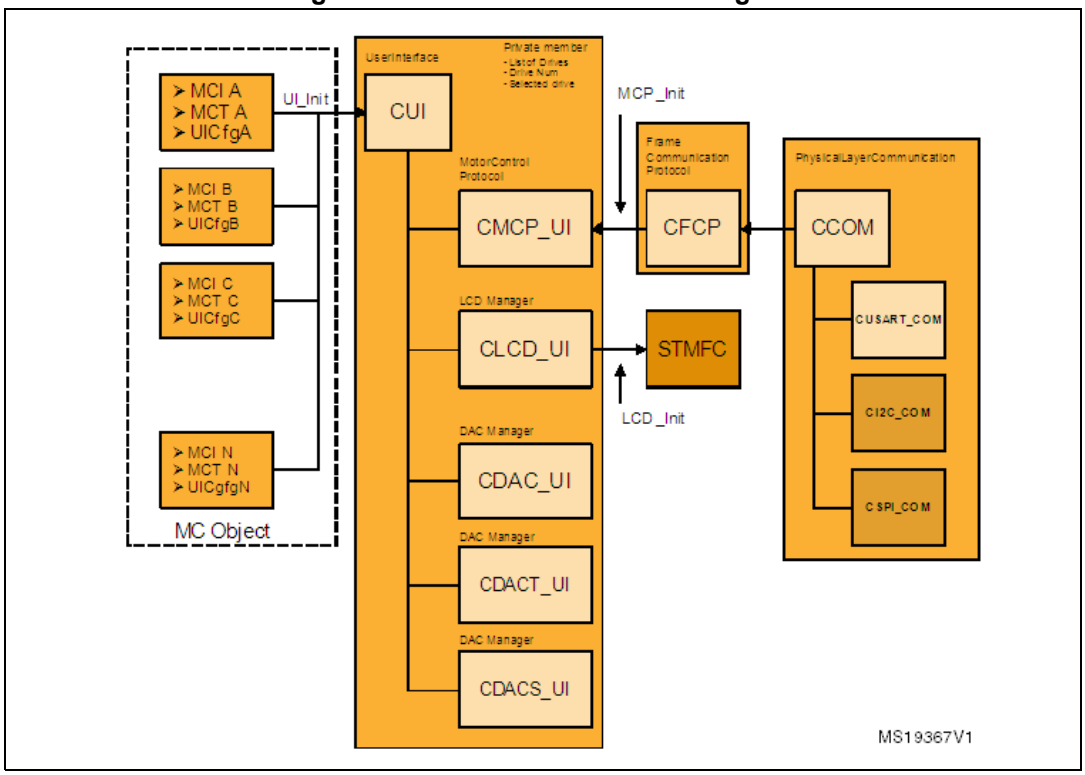
This section describes the details of the User interface layer. This is the highest software level present in the released STM32 PMSM FOC Library.

The user interface class (CUI) manages the interaction between the user and the motor control library (MC Library) via the motor control application layer (MC Application).

In the current implementation, the user interaction can be performed by any of the following devices: digital to analog converter (DAC), LCD display plus joystick, serial communication. For each of these devices, one or more derived class of UI object have been implemented (see *Figure 117*):

- LCD Manager Class (CLCD_UI) is used to interact with the LCD color display. It has been implemented over the LCD graphical library STMFC written in C++ language.
- Motor control protocol (CMCP_UI) is used to manage serial communications. The serial communication is implemented over the Frame communication protocol class CFCP (Transport layer). The CFCP is, in turn, implemented over a physical layer communication class CCOM (Physical layer). Daughter classes of CCOM are CUSART_COM, CI2C_COM and CSPI_COM. Presently only the CUSART_COM, that implements the physical serial communication using the USART channel, has been implemented and only with a PC master microcontroller slave configuration.
- DAC manager (CDAC_UI) is used to manage the DAC outputs using a real DAC peripheral. This is the default setting when DAC output is enabled using the STM32F0xx, STM32F100 (Value line), STM32F103xE (High density), STM32F2xx, STM32F30x or STM32F4xx devices.

Figure 117. User interface block diagram



- The DAC manager (CDACT_UI) manages DAC outputs using a virtual DAC implemented with a filtered PWM output generated by a timer peripheral. This is the default setting when a DAC output is enabled using the STM32F103xB (Medium density) device.
- CDACS_UI does not perform a digital to analog conversion but sends the output variables through an SPI communication.

13.1 User interface class (CUI)

This class implements the interaction between the user and the motor control library (MC Library) using the motor control application layer (MC Application). In particular, the CUI object is to be used to read or write relevant motor control quantities (for example, Electrical torque, Motor speed) and to execute the motor control commands exported by the MC Application (for example, Start motor, execute speed or torque ramps, customize the startup). Any object of this class must be linked to a derived class object.

The user interface class requires the following steps (implemented inside the UI_Init. method):

- Defines the number of motor drives managed by user interface objects. The implementation of the MC firmware manages at most two motor drives. The CUI can manage N drivers.
- Creates the link between MC tuning (MCT) MC interface (MCI) objects and user interface objects.

  See *Section 10.1: MCInterfaceClass* and *Section 10.2: MCTuningClass* for more information about MCI and MCT.
- Configures the options of user interface objects. See *Section 13.2: User interface configuration*.

Once initialized, the UI object is able to:

- Get and set the selected motor control drive that the UI operates on (UI_GetSlectedMC/UI_SelectMC). For example, UI_SelectMC is required in the case of a dual motor control, in order to select the active drive to which commands are applied (for example, Set/Get register, start motor).
- Get and set registers (UI_SetReg/UI_GetReg). A register is a relevant MC quantity that can be exported from, or imposed to, MC objects through MCI / MCT. The list of this

quantity MC_PROTOCOL_REG_xxx is exported by UserInterfaceClass.h. See *STM32 FOC PMSM FW library v3_3 developer Help file.chm*.

For example, to set up the proportional term of the speed controller of the second motor:

a) Obtain the oMCT and oMCI object through GetMCIList, GetMCTList functions, exported by MCTasks.h. The oMCI and oMCT are two arrays of objects.

```
CMCI oMCI[MC_NUM];
CMCT oMCT[MC_NUM];
...
GetMCIList(oMCI);
GeMCTList(oMCT);
...
```

b) Instantiate and initialize a CUI object.

```
oUI = UI_NewObject(MC_NULL);
UI_Init(oUI, MC_NUM, oMCI, oMCT, MC_NULL);
```

c) Select the motor drives

```
UI_SelectMC(oUI, 2);
```

d) Set the MC_PROTOCOL_REG_SPEED_KP register value.

```
UI_SetReg(oUI, MC_PROTOCOL_REG_SPEED_KP, <Desired value>);
```

A similar sequence can be used to get values from MC objects replacing the UI_SetReg method with the UI_GetReg method.

- Execute an MC command (UI_ExecCmd). The list of available MC commands MC_PROTOCOL_CMD_xxx is exported by UserInterfaceClass.h. See STM32 FOC PMSM FW library developer Help file.chm.

  For example, to execute a Start command to the first motor:

  a) Obtain the oMCT and oMCI object through GetMCIList, GetMCTList functions, exported by MCTasks.h. The oMCI and oMCT are two arrays of objects.

```
CMCI oMCI[MC_NUM];
CMCT oMCT[MC_NUM];
...
GetMCIList(oMCI);
GeMCTList(oMCT);
...
```

  b) Instantiate and initialize a CUI object.

```
oUI = UI_NewObject(MC_NULL);
UI_Init(oUI, MC_NUM, oMCI, oMCT, MC_NULL);
```

  c) Select the motor drives

```
UI_SelectMC(oUI, 2);
```

  d) Provide a command (for example, Start motor).

```
UI_ExecCmd (oUI, MC_PROTOCOL_CMD_START_MOTOR);
```

- Execute torque and speed ramps, set the current reference, and set or get revup data. See *STM32 FOC PMSM FW library developer Help file.chm*.
- Execute specific functions dedicated to CDAC objects. See *Section 13.7: DAC manager class (CDACx_UI)*.

Note: All derived classes of CUI act on MCI and MCT objects through the CUI methods. For instance, the LCD manager updates a motor control quantity calling UI_SetReg method and so on.

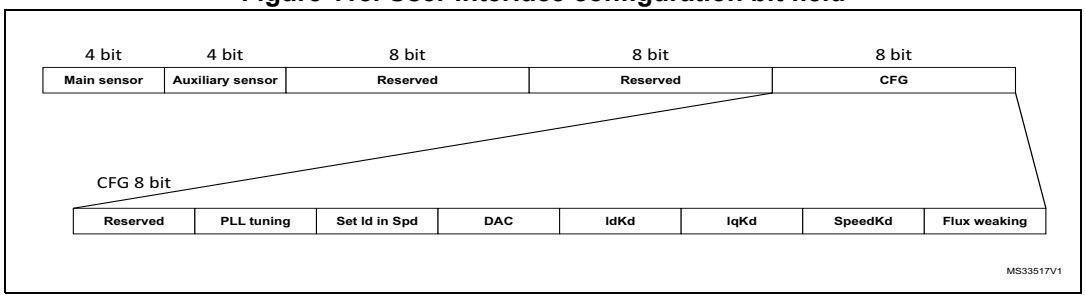
13.2 User interface configuration

A user interface object and its derivatives are configured using a 32-bit configuration value (see *Figure 118*).

The first byte of this register contains the sensor configuration. Each sensor is defined using 4 bits. The values UI_SCODE_xxx are exported by UserInterfaceClass.h. See *Table 32*.

The first 4-bit defines the main speed and position sensor. The second 4-bit defines the auxiliary speed and position sensor. 1

Figure 118. User interface configuration bit field



The remaining bit field values UI_CFGOPT_xxx are exported by UserInterfaceClass.h. See *Table 33*.

To configure the user interface object, the configuration should be passed in the UI_Init function as the 5th parameter. The 5th parameter of the UI_Init function is an array of configuration values, one for each motor drive.

Note: The 32-bit configuration value is automatically computed by a preprocessor in the Parameters conversion.h file, based on the configuration present in the System & Drive Params folder. It can be manually edited by the user.

Table 32. User interface configuration - Sensor codes

Code	Description
UI_SCODE_HALL	This code identifies the Hall sensor
UI_SCODE_ENC	This code identifies the Encoder sensor
UI_SCODE_STO_PLL	This code identifies the State observer + PLL sensor
UI_SCODE_STO_CR	This code identifies the State observer + CORDIC sensor

Table 33. User interface configuration - CFG bit descriptions

Code	Description
UI_CFGOPT_NONE	Enable this option when no other option is selected
UI_CFGOPT_FW	Enable this option when the flux weakening is enabled in the MC firmware

Table 33. User interface configuration - CFG bit descriptions

Code	Description
UI_CFGOPT_SPEED_KD	Enable this option when the speed controller has a derivative action
UI_CFGOPT_Iq_KD	Enable this option when the I_q controller has a derivative action
UI_CFGOPT_Id_KD	Enable this option when the I_d controller has a derivative action
UI_CFGOPT_DAC	Enable this option if a DAC object is associated with the UI
UI_CFGOPT_SETIDINSPDMODE	Enable this option to allow setting the I_d reference when MC is in speed mode
UI_CFGOPT_PLLTUNING	Enable this option to allow the PLL KP and KI setting

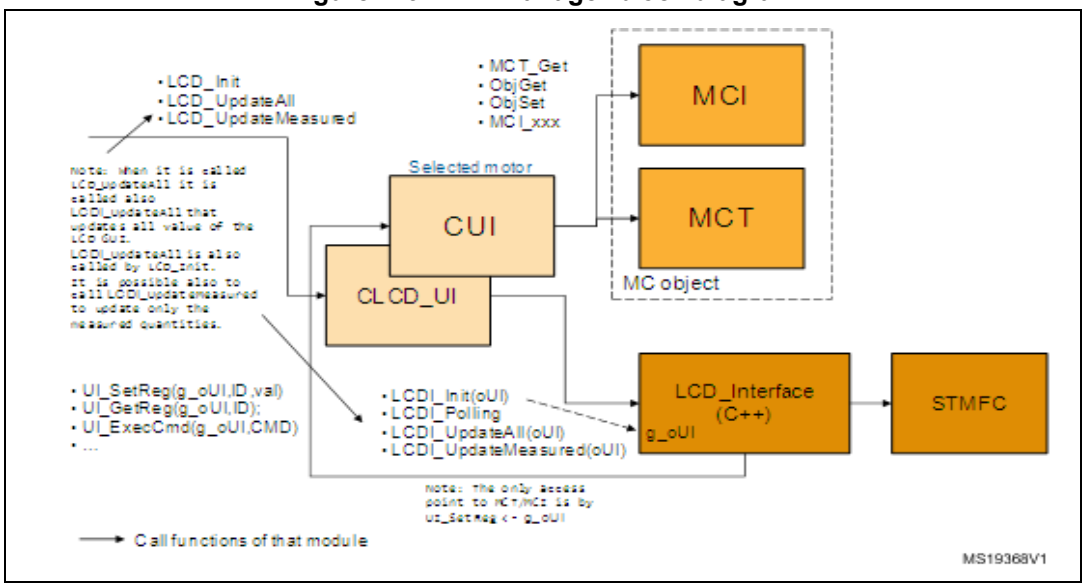
13.3 LCD manager class (CLCD_UI)

This is a derived class of UI that implements the management of the LCD screen. It is based on the LCD graphical library STMFC written in C++ language.

A functional block diagram of LCD manager is shown in *Figure 119*.

The MC objects (MCI/MCT) are linked to the LCD manager by the UI_Init and are accessed only by base class methods.

Figure 119. LCD manager block diagram



The LCD_Interface is a module written in C++ that performs the interface between UI objects and the STMFC library.

When LCD_Init or LCD_UpdateAll are called, the LCDI_UpdateAll method is also called and updates all values of the LCD GUI. You can also call LCDI_UpdateMesured to update only the measured quantity (the quantity that changes inside the MC object itself, such as measured speed, measure I_q).

13.4 Using the LCD manager

To use the LCD manager, you must:

1. Obtain the oMCT and oMCI object through GetMCIList, GetMCTList functions, exported by MCTasks.h. The oMCI and oMCT are two arrays of objects.

```
CMCI oMCI[MC_NUM];
CMCT oMCT[MC_NUM];
...
GetMCIList(oMCI);
GeMCTList(oMCT);
    ...
```

2. Instantiate and initialize an CLCD_UI object.

```
CLCD_UI oLCD = LCD_NewObject(MC_NULL);
UI_Init((CUI)oLCD, MC_NUM, oMCI, oMCT, pUICfg);
LCD_Init(oLCD, (CUI)oDAC, s_fwVer);
```

   Note that you must call both UI_Init and LCD_Init. LCD_Init must be called after UI_Init.
   - pUICfg is the user interface configurations array. See *Section 13.2: User interface configuration*.
   - oDAC is the related DAC object that should be driven by the LCD manager. This DAC object should be correctly instantiated before the LCD_Init calls. See the DAC manager class (CDAC).
   - s_fwVer is a string that will be displayed in the LCD (See *Figure 92: STM32 Motor Control demonstration project welcome message*) containing both the Firmware version and Release version; it must be separated by the 0x0 character.
3. Periodically call the LCD_UpdateMeasured method. This updates LCD GUI variables and calls the LCD_Exec method that performs the LCD screen refresh.

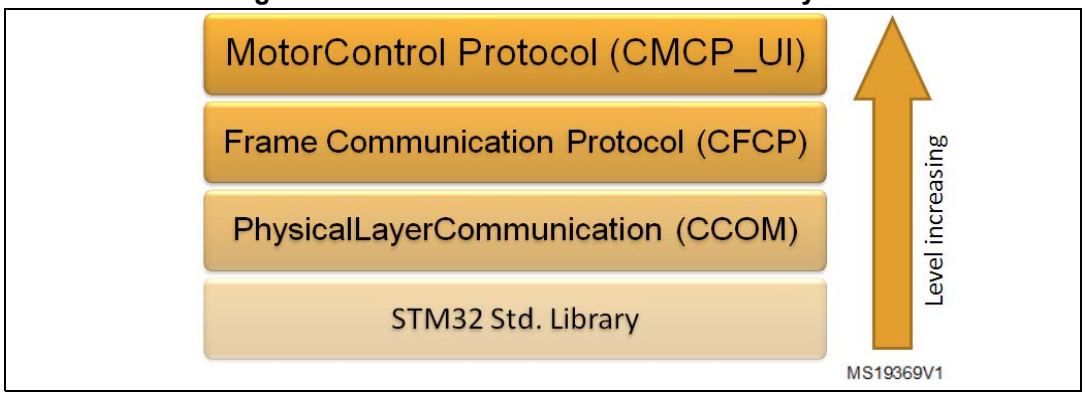
```
LCD_Exec(oLCD);
LCD_UpdateMeasured(oLCD);
```

These functions are performed inside UITask.c. The LCD refresh also uses Timebase.c or RTOS.

13.5 Motor control protocol class (CMCP_UI)

This is a derived class of UI that is based on the serial communication. This class is on the top layer of the serial communication architecture (See *Figure 120*) and manages the highest level of the motor control protocol.

Figure 120. Serial communication software layers



The frame communication protocol (CFCP) implements the transport layer of the serial communication. It is responsible for the correct transfer of the information, CRC checksum and so on.

The CCOM class implements the physical layer, through its derivatives. For each physical communication channel, there is a specific derivative of the CCOM object. Only the USART channel has been implemented so far (by CUSART_COM class).

13.6 Using the motor control protocol

1. Obtain the oMCT and oMCI object through GetMCIList and GetMCTList functions, exported by MCTasks.h. oMCI and oMCT are two arrays of objects.

```
CMCI oMCI[MC_NUM];
CMCT oMCT[MC_NUM];
...
GetMCIList(oMCI);
GeMCTList(oMCT);
...
```

2. MCP parameters, Frame parameters and USART parameters are defined in USARTParams.h and can be modified if required.
3. Instantiate and initialize CMCP_UI, CFCP, and COM objects.

```
CMCP_UI oMCP = MCP_NewObject(MC_NULL,&MCPParams);
CFCP oFCP = FCP_NewObject(&FrameParams_str);
CUSART_COM oUSART = USART_NewObject(&USARTParams_str);

FCP_Init(oFCP, (CCOM)oUSART);
MCP_Init(oMCP, oFCP, oDAC, s_fwVer);
UI_Init((CUI)oMCP, bMCNum, oMCIList, oMCTList, pUICfg);
```

   Note that you must call both MCP_Init and UI_Init.
   - pUICfg is the user interface configurations array. See *Section 13.2: User interface configuration*.
   - oDAC is the related DAC object that should be driven by the LCD manager. This DAC object should be correctly instantiated before the LCD_Init calls. See the DAC manager class (CDAC).
   - s_fwVer is a string containing the Firmware version and Release version. It is separated by the 0x0 character that will be sent back to PC after a "get firmware info" command.
4. Manage the serial communication timeout. After the first byte has been received by the microcontroller, a timeout timer is started. If all the expected bytes of the frame sequence have been received, the timeout counter is stopped. On the contrary, if the timeout occurs, the timeout event must be handled calling:

```
Exec_UI_IRQ_Handler(UI_IRQ_USART,3,0);
```

   These functions are performed inside UITask.c. The time base for serial communication timeout also uses Timebase.c or RTOS, by default.

13.7 DAC manager class (CDACx_UI)

There are three derivatives of CUI that implement DAC management:

- DAC_UI (DAC_UI): DAC peripheral used as the output.
- DACRCTIMER_UI (DACT_UI): General purpose timer used and output together with an RC filter.
- DACSPI_UI (DACS_UI): SPI peripheral used as the output. The data can be codified by an oscilloscope, for instance.

For each DAC class, the number of channels (two) is defined. The DAC variables are predefined motor control variables or user defined variables that can be output by DAC objects. DAC variables can be any MC_PROTOCOL_REG_xxx value exported by UserInterfaceClass.h. *Table 34* describes a set of relevant motor control quantities.

Table 34. Description of relevant DAC variables

Variable name	Description
MC_PROTOCOL_REG_I_A	Measured phase A motor current.
MC_PROTOCOL_REG_I_B	Measured phase B motor current.
MC_PROTOCOL_REG_I_ALPHA	Measured alpha component of motor phase's current expressed in alpha/beta reference.
MC_PROTOCOL_REG_I_BETA	Measured beta component of motor phase's current expressed in alpha/beta reference.
MC_PROTOCOL_REG_I_Q	Measured "q" component of motor phase's current expressed in q/d reference.
MC_PROTOCOL_REG_I_D	Measured "d" component of motor phase's current expressed in q/d reference.
MC_PROTOCOL_REG_I_Q_REF	Target "q" component of motor phase's current expressed in q/d reference.
MC_PROTOCOL_REG_I_D_REF	Target "d" component of motor phase's current expressed in q/d reference.
MC_PROTOCOL_REG_V_Q	Forced "q" component of motor phase's voltage expressed in q/d reference.
MC_PROTOCOL_REG_V_D	Forced "d" component of motor phase's voltage expressed in q/d reference.
MC_PROTOCOL_REG_V_ALPHA	Forced alpha component of motor phase's voltage expressed in alpha/beta reference.
MC_PROTOCOL_REG_V_BETA	Forced beta component of motor phase's voltage expressed in alpha/beta reference.
MC_PROTOCOL_REG_MEAS_EL_ANGLE	Measured motor electrical angle. This variable is related to a "real" sensor (encoder, Hall) configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_MEAS_ROT_SPEED	Measured motor speed. This variable is related to a "real" sensor (encoder, Hall) configured as a primary or auxiliary speed.
MC_PROTOCOL_REG_OBS_EL_ANGLE	Observed motor electrical angle. This variable is related to a "state observer + PLL" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_ROT_SPEED	Observed motor speed. This variable is related to a "state observer+ PLL" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_I_ALPHA	Observed alpha component of motor phase's current expressed in alpha/beta reference. This variable is related to a "state observer + PLL" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_I_BETA	Observed beta component of motor phase's current expressed in alpha/beta reference. This variable is related to a "state observer + PLL" sensor configured as a primary or auxiliary speed sensor.

Table 34. Description of relevant DAC variables (continued)

Variable name	Description
MC_PROTOCOL_REG_OBS_BEMF_ALPHA	Observed alpha component of motor BEMF expressed in alpha/beta reference. This variable is related to a "state observer + PLL" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_BEMF_BETA	Observed beta component of motor BEMF expressed in alpha/beta reference. This variable is related to a "state observer + PLL" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_EL_ANGLE	Observed motor electrical angle. This variable is related to a "state observer + CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_ROT_SPEED	Observed motor speed. This variable is related to a "state observer+ CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_I_ALPHA	Observed alpha component of motor phase's current expressed in alpha/beta reference. This variable is related to a "state observer + CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_I_BETA	Observed beta component of motor phase's current expressed in alpha/beta reference. This variable is related to a "state observer + CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_BEMF_ALPHA	Observed alpha component of motor BEMF expressed in alpha/beta reference. This variable is related to a "state observer + CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_OBS_CR_BEMF_BETA	Observed beta component of motor BEMF expressed in alpha/beta reference. This variable is related to a "state observer + CORDIC" sensor configured as a primary or auxiliary speed sensor.
MC_PROTOCOL_REG_DAC_USER1	User defined DAC variable. *Section 13.9* describes how to configure user defined DAC variables.
MC_PROTOCOL_REG_DAC_USER2	User defined DAC variable. *Section 13.9* describes how to configure user defined DAC variables.

Each DAC variable can be selected to be output to a DAC channel. The DAC channel is physically put in the output by calling the UI_DACExec method.

13.8 Using the DAC manager

1. Obtain the oMCT and oMCI object through GetMCIList, and GetMCTList functions, exported by MCTasks.h. oMCI and oMCT are two arrays of objects.

```
CMCI oMCI[MC_NUM];
CMCT oMCT[MC_NUM];
...
GetMCIList(oMCI);
GeMCTList(oMCT);
...
```

2. Instantiate and initialize CDACx_UI objects. Choose the correct CDACx_UI object based on the hardware setting.

```
CDACx_UI oDAC = DACT_NewObject(MC_NULL,MC_NULL);
UI_Init((CUI)oDAC, bMCNum, oMCIList, oMCTList, pUICfg);
UI_DACInit((CUI)oDAC);
```

   Note that you must call both UI_Init and UI_DACInit.

   pUICfg is the user interface configuration array. See *Section 13.2: User interface configuration*.

3. Configure the DAC variables for each DAC channel.

```
UI_DACChannelConfig((CUI)oDAC, DAC_CH0, MC_PROTOCOL_REG_I_A);
UI_DACChannelConfig((CUI)oDAC, DAC_CH1, MC_PROTOCOL_REG_I_B);
```

   In this case, the motor current Ia and Ib will be put in output.

4. Periodically update the DAC output by calling the UI_DACExec method that performs the update of DAC channel into the physical output.

These functions are performed inside UITask.c. For the update, the DAC outputs also use stm32fxxx_MC_it.c.

Note: The default variables that is selected after each reset of the microcontroller can be selected in the ST MC Workbench->Control stage->DAC

13.9 How to configure the user defined DAC variables

Two user-defined DAC variables can be put as analog outputs. These variables enable custom debugging on variables that change in real-time, and monitor the correlation with relevant motor control values such as real/measured currents. You cannot put more than two DAC variables (motor control predefined or user-defined) in the output.

To store the user value in a user-defined DAC variable, follow these steps:

1. Obtain the oDAC DAC objects through the GetDAC function exported by UITask.h.
2. Call the UI_DACSetUserChannelValue method of a CUI object to update the content of a user defined DAC variable.

```
UI_DACSetUserChannelValue(oDAC,0,hUser1);
```

   In this case, the hUser1 value is set in the first (0) user-defined DAC variable.

3. Configure user-defined DAC variables to be put in output using the UI_DACChannelConfig method, or put the user-defined variables in the output using

the LCD/Joystick interface (see *Section 11.2.3: Configuration and debug page*).

```
UI_DACChannelConfig((CUI)oDAC, DAC_CH0,
MC_PROTOCOL_REG_DAC_USER1);
```

4. The user value is physically put in the output when UI_DACExec is executed. UITask.c performs the following:

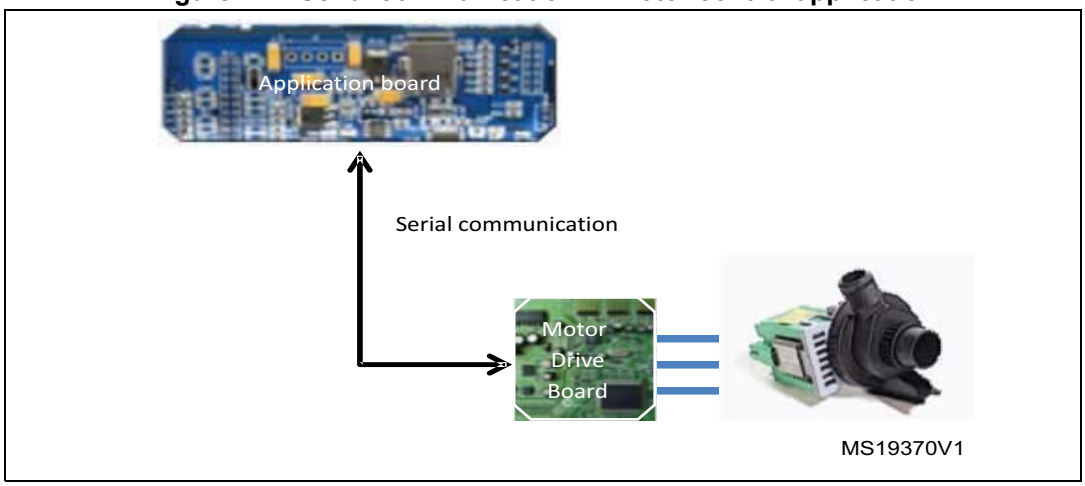
```
UI_DACExec((CUI)oDAC);
```

14 Serial communication class overview

Applications on the market, that require an electrical motor to be driven, usually have the electronics split in two parts: application board and motor drive board.

To drive the system correctly, the application board requires a method to send a command to the motor drive board and get a feedback. This is usually performed using a serial communication. See *Figure 121*.

Figure 121. Serial communication in motor control application



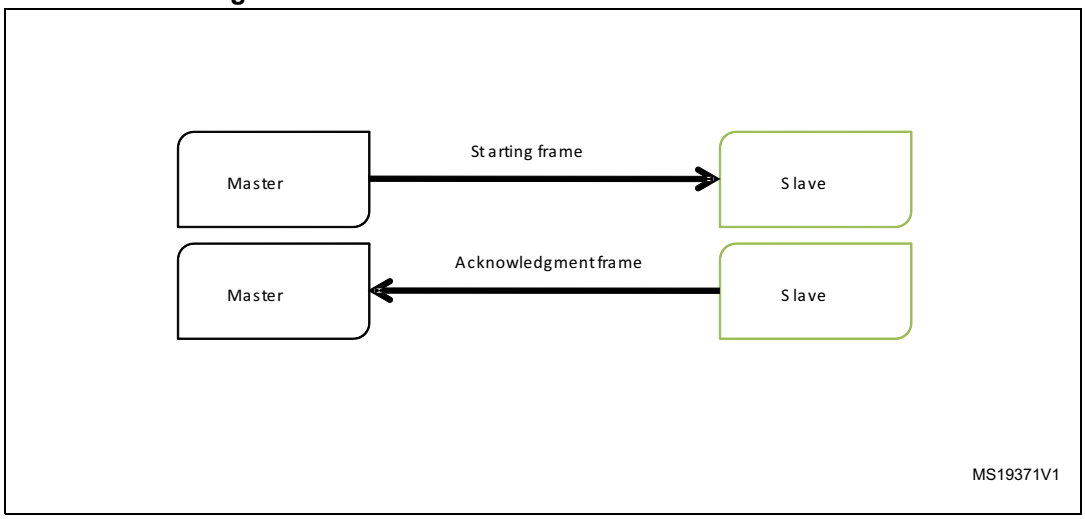
To target this kind of application, a dedicated serial communication protocol has been developed for real-time data exchange. The aim of this protocol is to implement the feature requested by motor control related applications. The implemented protocol is called motor control protocol (MCP).

MCP makes it possible to send commands such as start/stop motor and set the target speed to the STM32 FOC motor control firmware, and also to tune in real-time relevant control variables such as PI coefficients. It is also possible to monitor relevant quantities, such as the speed of the motor or the bus voltage present in the board related to the controlled system.

The implemented communication protocol is based on a master-slave architecture in which the motor control firmware, running on an STM32 microcontroller, is the slave.

The master, usually a PC or another microcontroller present on a master board, can start the communication at any time by sending the first communication frame to the slave. The slave answers this frame with the acknowledge frame. See *Figure 122*.

Figure 122. Master-slave communication architecture



The implemented MCP is based on the physical layer that uses the USART communication.

A generic starting frame (*Table 35*) is composed of:

- Frame_start: this byte defines the type of starting frame. The least significant 5 bits indicate the frame identifier. The most significant 3 bits indicate the motor selection. See *Table 36*.
- Payload_Length: the total number of bytes that compose the frame payload
- Payload_ID: first byte of the payload that contains the identifier of payload. Not necessary if not required by this type of frame.
- Payload[x]: the remaining payload content. Not necessary if not required by this type of frame.
- CRC: byte used for cyclic redundancy check.

The CRC byte is computed as follows:

$$Total = (unsigned16bit)\left(FrameID + PayloadLength + \Sigma_{i=0}^{n} Payload[i]\right)$$

$$CRC = (unsigned8bit)(HighByte(Total) + LowByte(Total))$$

Table 35. Generic starting frame

FRAME_START	PAYLOAD_LENGTH	PAYLOAD_ID	PAYLOAD[0]	...	PAYLOAD[n]	CRC

Table 38 shows the list of possible starting frames.

Table 36. FRAME_START byte

	Motor			FRAME_ID				
FRAME_START								
	7	6	5	4	3	2	1	0

Table 37. FRAME_START motor bits

FRAME_ID	Motor bit
000	The command is applied to the last motor selected
001	The command is applied to motor 1; motor 1 is selected from now on
010	The command is applied to motor 2; motor 2 is selected from now on (this can be accepted only in dual drive)

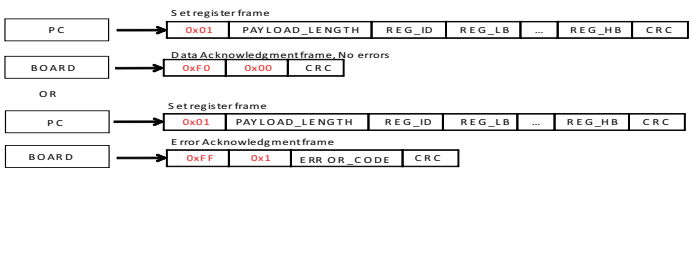
Table 38. Starting frame codes

Frame_ID	Description
0x01	Set register frame. It is used to write a value into a relevant motor control variable. See Set register frame.
0x02	Get register frame. It is used to read a value from a relevant motor control variable. See Get register frame.
0x03	Execute command frame. It is used to send a command to the motor control object. See Execute command frame.
0x06	Get board info. It is used to retrieve information about the firmware currently running on the microcontroller.
0x07	Exec ramp. It is used to execute a speed ramp. See *Section 14.4: Execute ramp frame*.
0x08	Get revup data. It is used to retrieve the revup parameters. See *Section 14.5: Get revup data frame*.
0x09	Set revup data. It is used to set the revup parameters. See *Section 14.6: Set revup data frame*.
0x0A	Set current references. It is used to set the current reference. See *Section 14.7: Set current references frame*

14.1 Set register frame

The set register frame (*Figure 123*) is sent by the master to write a value into a relevant motor control variable.

Figure 123. Set register frame



The payload length depends on REG_ID (See *Table 39*).

Reg Id indicates the register to be updated.

The remaining payload contains the value to be updated, starting from the least significant byte to the most significant byte.

The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. The payload of this Data Acknowledgment frame is zero.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39*.

Table 39. List of error codes

Error code	Description
0x01	BAD Frame ID. The Frame ID has not been recognized by the firmware.
0x02	Write on read-only. The master wants to write on a read-only register.
0x03	Read not allowed. The value cannot be read.
0x04	Bad target drive. The target motor is not supported by the firmware.
0x05	Out of range. The value used in the frame is outside the range expected by the firmware.
0x07	Bad command ID. The command ID has not been recognized.
0x08	Overrun error. The frame has not been received correctly because the transmission speed is too fast.
0x09	Timeout error. The frame has not been received correctly and a timeout occurs. This kind of error usually occurs when the frame is not correct or is not correctly recognized by the firmware.
0x0A	Bad CRC. The computed CRC is not equal to the received CRC byte.
0x0B	Bad target drive. The target motor is not supported by the firmware.

Table 40 indicates the following for each of the relevant motor control registers:

- Type (u8 8-bit unsigned, u16 16-bit unsigned, u32 32-bit unsigned, s16 16-bit signed, s32 32-bit signed)
- Payload length in Set register frame
- allowed access (R read, W write)
- Reg Id

Table 40. List of relevant motor control registers

Register name	Type	Payload length	Access	Reg Id
Target motor	u8	2	RW	0x00
Flags	u32	5	R	0x01
Status	u8	2	R	0x02
Control mode	u8	2	RW	0x03
Speed reference	s32	5	R	0x04

Table 40. List of relevant motor control registers (continued)

Register name	Type	Payload length	Access	Reg Id
Speed KP	u16	3	RW	0x05
Speed KI	u16	3	RW	0x06
Speed KD	u16	3	RW	0x07
Torque reference (I_q)	s16	3	RW	0x08
Torque KP	u16	3	RW	0x09
Torque KI	u16	3	RW	0x0A
Torque KD	u16	3	RW	0x0B
Flux reference (I_d)	s16	3	RW	0x0C
Flux KP	u16	3	RW	0x1D
Flux KI	u16	3	RW	0x1E
Flux KD	u16	3	RW	0x1F
Observer C1	s16	3	RW	0x10
Observer C2	s16	3	RW	0x11
Cordic Observer C1	s16	3	RW	0x12
Cordic Observer C2	s16	3	RW	0x13
PLL KI	u16	3	RW	0x14
PLL KP	u16	3	RW	0x15
Flux weakening KP	u16	3	RW	0x16
Flux weakening KI	u16	3	RW	0x17
Flux weakening BUS Voltage allowed percentage reference	u16	3	RW	0x18
Bus Voltage	u16	3	R	0x19
Heatsink temperature	u16	3	R	0x1A
Motor power	u16	3	R	0x1B
DAC Out 1	u8	2	RW	0x1C
DAC Out 2	u8	2	RW	0x1D
Speed measured	s32	5	R	0x1E
Torque measured (I_q)	s16	3	R	0x1F
Flux measured (I_d)	s16	3	R	0x20
Flux weakening BUS Voltage allowed percentage measured	u16	3	R	0x21
Revup stage numbers	u8	2	R	0x22
Maximum application speed	u32	5	R	0x3F
Minimum application speed	u32	5	R	0x40

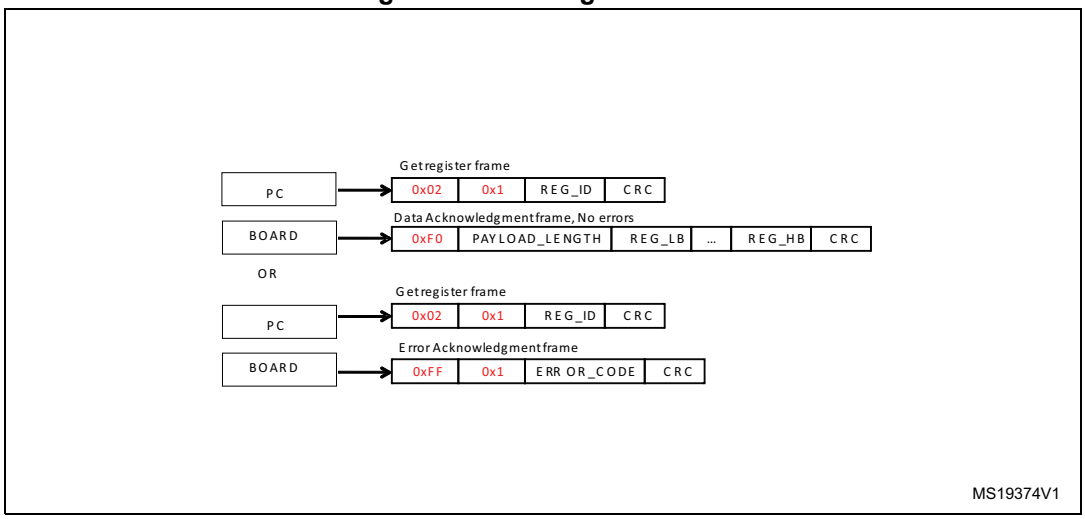
Table 40. List of relevant motor control registers (continued)

Register name	Type	Payload length	Access	Reg Id
Iq reference in speed mode	s16	3	W	0x41
Expected BEMF level (PLL)	s16	3	R	0x42
Observed BEMF level (PLL)	s16	3	R	0x43
Expected BEMF level (CORDIC)	s16	3	R	0x44
Observed BEMF level (CORDIC)	s16	3	R	0x45
Feedforward (1Q)	s32	5	RW	0x46
Feedforward (1D)	s32	5	RW	0x47
Feedforward (2)	s32	5	RW	0x48
Feedforward (VQ)	s16	3	R	0x49
Feedforward (VD)	s16	3	R	0x4A
Feedforward (VQ PI out)	s16	3	R	0x4B
Feedforward (VD PI out)	s16	3	R	0x4C
Ramp final speed	s32	5	RW	0x5B
Ramp duration	u16	3	RW	0x5C

14.2 Get register frame

The get register frame (*Figure 124*) is sent by the master to read a value from a relevant motor control variable.

Figure 124. Get register frame



Payload length is always 1.

Reg Id indicates the register to be queried (See *Table 40*).

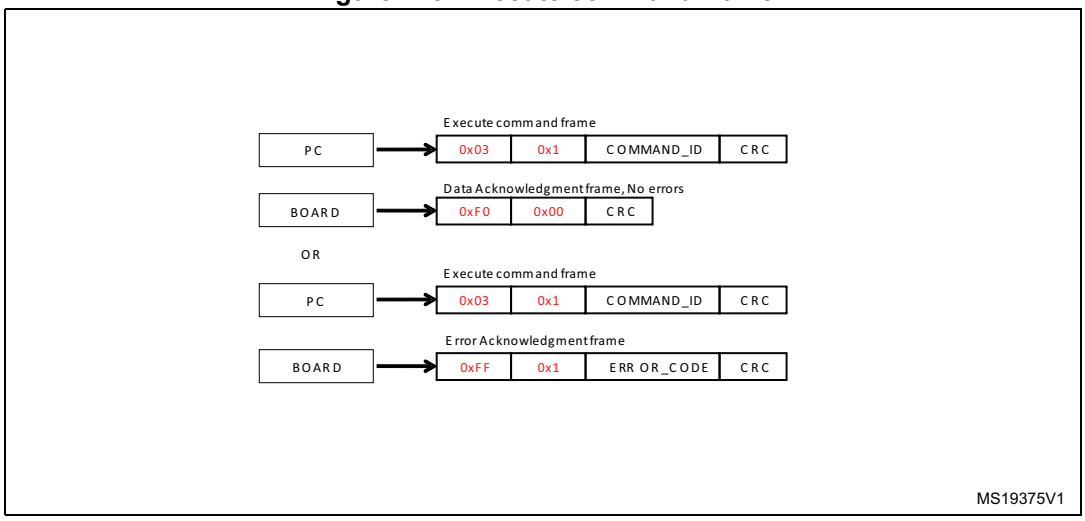
The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. In this case, the returned value is embedded in the Data Acknowledgment frame. The size of the payload depends on Reg Id and is equal to the Payload length present in *Table 40* minus 1. The value is returned starting from the least significant byte to the most significant byte.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39*.

14.3 Execute command frame

The execute command frame (*Figure 125*) is sent by the master to the motor control firmware to request the execution of a specific command.

Figure 125. Execute command frame



Payload length is always 1.

Command Id indicates the requested command (See *Table 41*).

The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. In this case, the returned value embedded in the Data Acknowledgment frame is an echo of the same Command Id. The size of payload is always 1.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39*.

Table 41 indicates the list of commands:

Table 41. List of commands

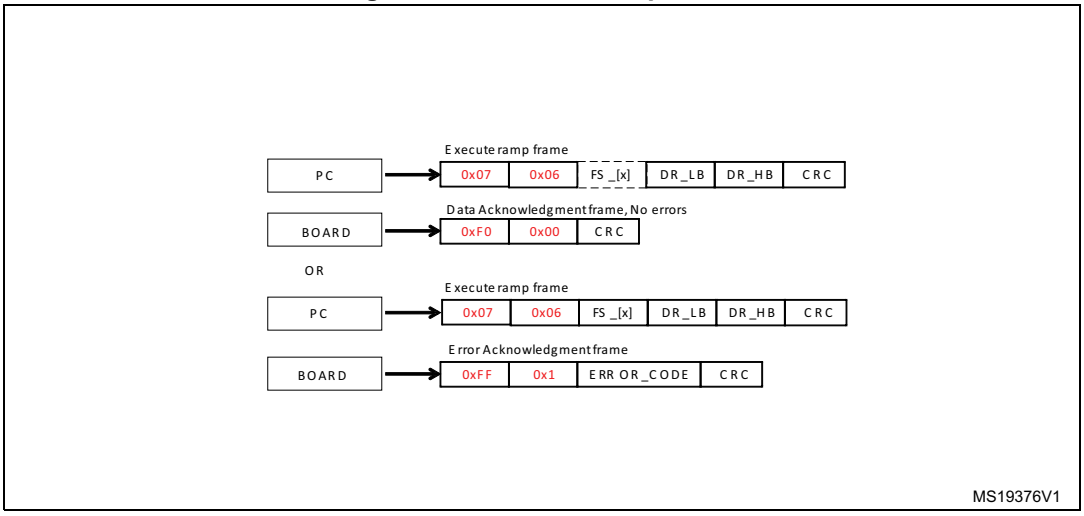
Command	Command ID	Description
Start Motor	0x01	Indicates the user request to start the motor regardless the state of the motor.
Stop Motor	0x02	Indicates the user request to stop the motor regardless the state of the motor.
Stop Ramp	0x03	Indicates the user request to stop the execution of the speed ramp that is currently executed
Start/Stop	0x06	Indicates the user request to start the motor if the motor is still, or to stop the motor if it runs.
Fault Ack	0x07	Communicates the user acknowledges of the occurred fault conditions.
Encoder Align	0x08	Indicates the user request to perform the encoder alignment procedure.

14.4 Execute ramp frame

The execute ramp frame (*Figure 126*) is sent by the master to the motor control firmware, to request the execution of a speed ramp.

A speed ramp always starts from the current motor speed, and is defined by a duration and a final speed. See *Figure 127*.

Figure 126. Execute ramp frame



Payload length is always 6.

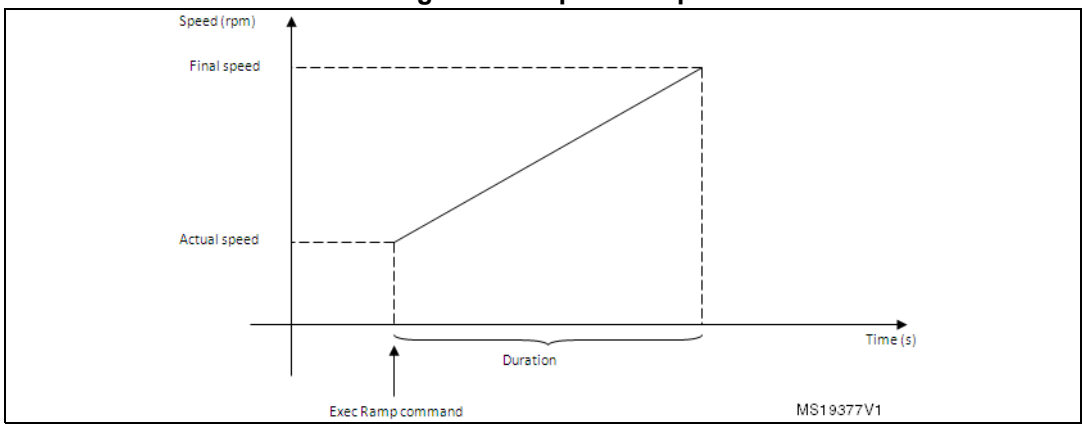
The four bytes FS[x] represent the final speed expressed in rpm least significant byte and most significant byte.

DR_LB and DR_HB represent the duration expressed in milliseconds, respectively least significant byte and most significant byte.

The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. The payload of this Data Acknowledgment frame will be zero.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39: List of error codes*.

Figure 127. Speed ramp

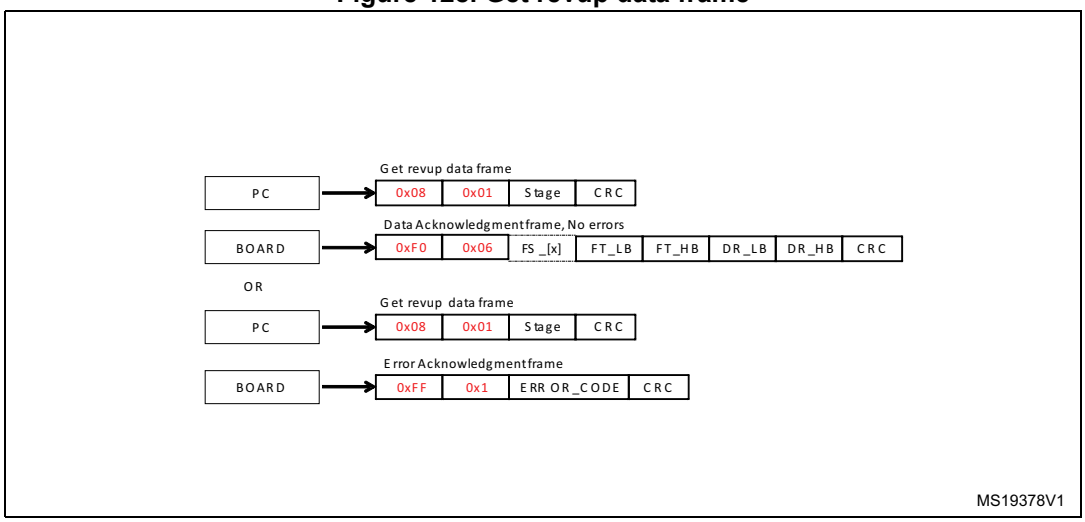


14.5 Get revup data frame

The get revup data frame (*Figure 128*) is sent by the master to retrieve the current revup parameters.

Revup sequence is a set of commands performed by the motor control firmware to drive the motor from zero speed up to run condition. It is mandatory for a sensorless configuration. The sequence is split into several stages; a duration, final speed and final torque (actually I_q reference) can be set up for each stage. See *Figure 129*.

Figure 128. Get revup data frame



The master indicates the requested stage parameter sending the stage number in the starting frame payload. Payload length is always 1.

The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. In this case, the returned values are embedded in the Data Acknowledgment frame. The payload size of this Data Acknowledgment frame is always 8.

  The four bytes FS[x] represent the final speed of the selected stage expressed in rpm, from the least significant byte to the most significant byte.

  FT_LB and FT_HB represent the final torque of the selected stage expressed in digit, respectively the least significant byte and the most significant byte.

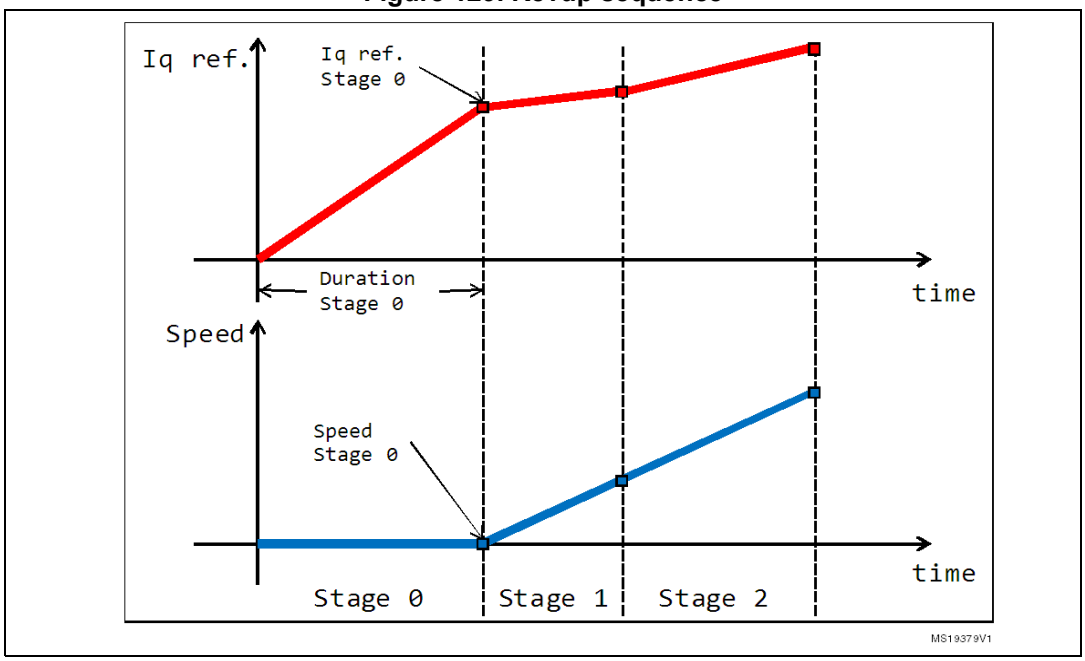
Note: To convert current expressed in Amps to current expressed in digit, use the formula:

Current(digit)=[Current(Amp)×65536×R_Shunt×A_OP]/V_(DD Micro)

DR_LB and DR_HB represent the duration of the selected stage expressed in milliseconds, respectively the least significant byte and the most significant byte.

- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39: List of error codes*.

Figure 129. Revup sequence

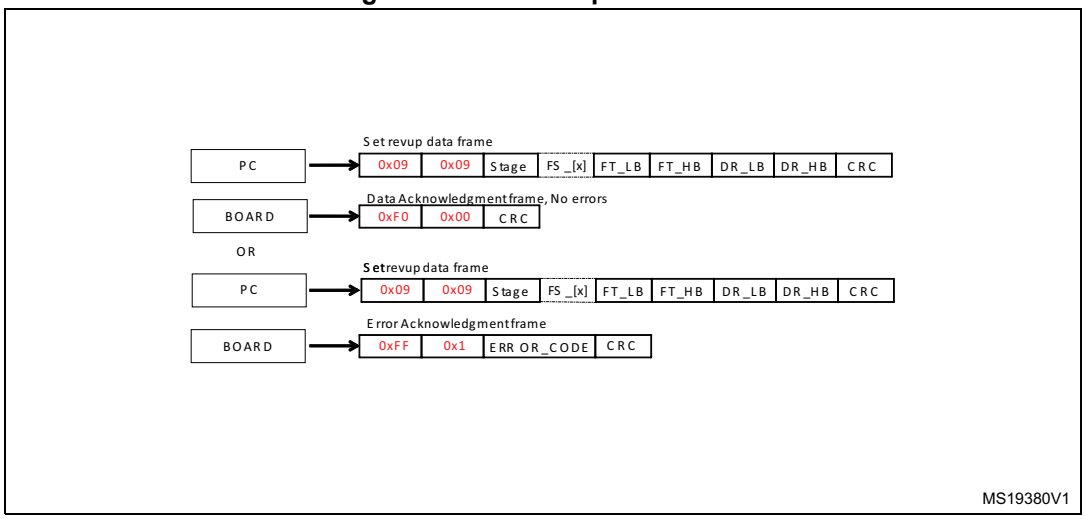


14.6 Set revup data frame

The set revup data frame (*Figure 130*) is sent by the master to modify the revup parameters.

Revup sequence is a set of commands performed by the motor control firmware to drive the motor from zero speed up to run condition. It is mandatory for a sensorless configuration. The sequence is split into several stages. For each stage, a duration, final speed and final torque (actually I_q reference) can be set up. See *Figure 129*.

Figure 130. Set revup data frame



The Master sends the requested stage parameter.

The payload length is always 9.

Stage is the revup stage that will be modified.

The four bytes FS[x] is the requested new final speed of the selected stage expressed in rpm, from the least significant byte to the most significant byte.

FT_LB and FT_HB are the requested new final torque of the selected stage expressed in digit, respectively the least significant byte and the most significant byte.

Note: To convert current expressed in Amps to current expressed in digit, it is possible to use the formula:

*Current(digit) = [Current(Amp) * 65536 * Rshunt * Aop] / Vdd micro.*

DR_LB and DR_HB is the requested new duration of the selected stage expressed in milliseconds, respectively the least significant byte and the most significant byte.

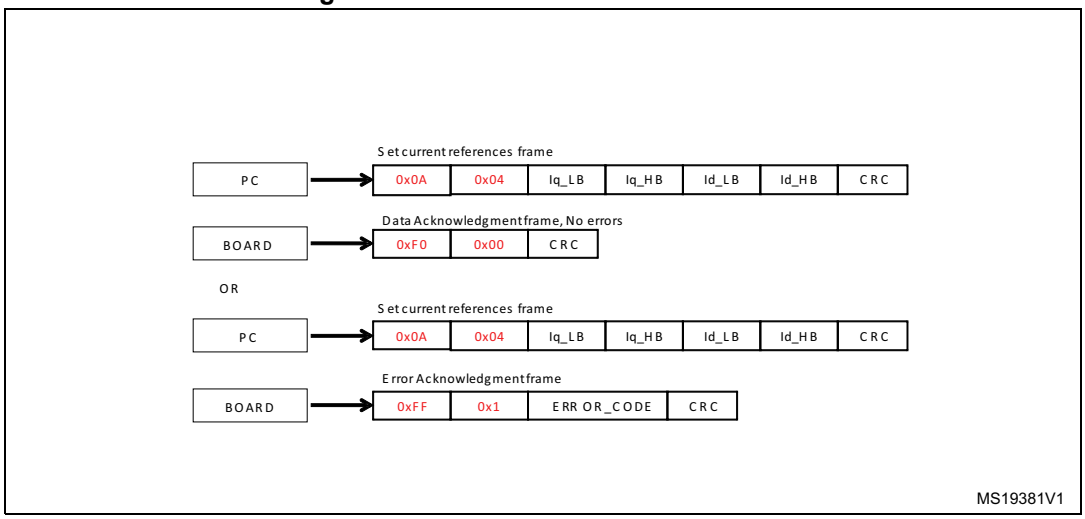
The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. The payload of this Data Acknowledgment frame will be zero.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39*.

14.7 Set current references frame

The set current references frame (*Figure 131*) is sent by the Master to modify the current references I_q, I_d.

Figure 131. Set current reference frame



The Master sends the requested current references.

The payload length is always 4.

Iq_LB and Iq_HB are the requested new I_q references expressed in digit, respectively the least significant byte and the most significant byte.

Id_LB and Id_HB are the requested new I_d reference expressed in digit, respectively the least significant byte and the most significant byte.

Note: To convert current expressed in Amps to current expressed in digit, it is possible to use the formula:

Current(digit)=[Current(Amp)×65536×R_Shunt×A_OP]/Vdd micro)

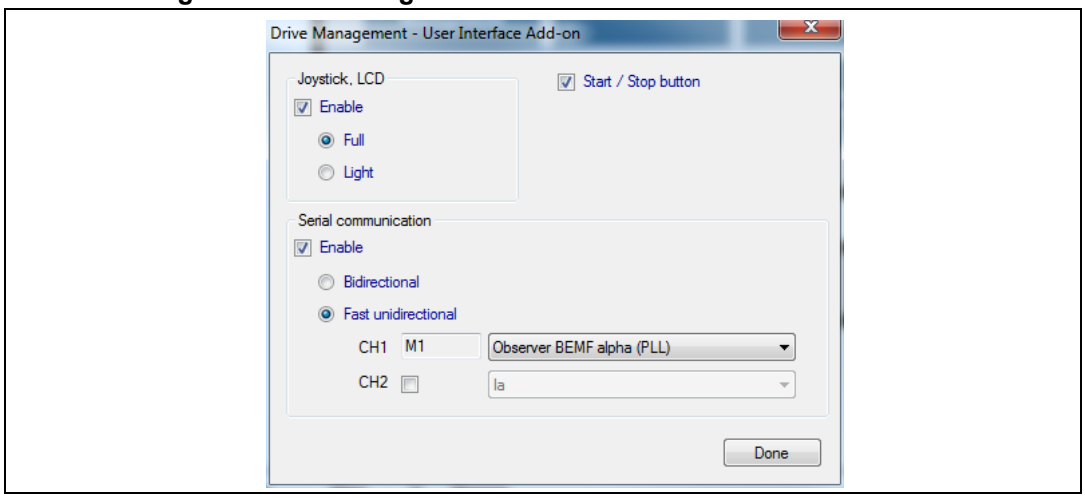
The Acknowledgment frame can be of two types:

- Data Acknowledgment frame, if the operation has been successfully completed. The payload of this Data Acknowledgment frame will be zero.
- Error Acknowledgment frame, if the operation has not been successfully completed by the firmware. The payload of this Error Acknowledgment frame is always 1. The list of error codes is shown in *Table 39: List of error codes*.

15 Fast serial communication

Fast unidirectional serial communication option is implemented in the STM32 FOC Firmware library and can be enabled in the ST MC Workbench checking "Enable" in the Drive Management - User Interface Add-on - Serial communication and select "Fast unidirectional" option like shown in *Figure 132*.

Figure 132. Enabling fast unidirectional serial communication



When enabled is possible also to select the quantity that have to be sent through serial communication among the relevant motor control variables (in a way similar to the list of DAC variables). Optionally two variables can be sent alternatively.

Note: This kind of serial communication is non supported by the real time communication of ST MC Workbench.

16 Document conventions

Table 42. List of abbreviations

Abbreviation	Definition
AC	Alternate Current
API	Application Programming Interface
B-EMF	Back Electromotive Force
CC-RAM	Core Coupled Memory Random Access Memory
CORDIC	COordinate Rotation DIgital Computer
DAC	Digital to Analog Converter
DC	Direct Current
FOC	Field Oriented Control
GUI	Graphical User Interface
I-PMSM	Internal Permanent Magnet Synchronous Motor
IC	Integrated Circuit
ICS	Isolated Current Sensor
IDE	Integrated Development Environment
MC	Motor Control
MCI	Motor Control Interface
MCT	Motor Control Tuning
MTPA	Maximum Torque Per Ampere
PGA	Programmable Gain Amplifier
PID controller	Proportional-Integral-Derivative controller
PLL	Phase-Locked Loop
PMSM	Permanent Magnet Synchronous Motor
SDK	Software Development Kit
SM-PMSM	Surface Mounted Permanent Magnet Synchronous Motor
SV PWM	Space Vector Pulse-Width Modulation
UI	User Interface

Appendix A Additional information

A.1 References

[1] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, Analysis of Electric Machinery and Drive Systems, Wiley-IEEE Press, 2002.

[2] T. A. Lipo and D. W. Novotny, Vector Control and Dynamics of AC Drives, Oxford University Press, 1996.

[3] S. Morimoto, Y. Takeda, T. Hirasa, K. Taniguchi, “Expansion of Operating Limits for Permanent Magnet Motor by Optimum Flux-Weakening”, Conference Record of the 1989 IEEE, pp. 51-56 (1989).

[4] J. Kim, S. Sul, “Speed control of Interior PM Synchronous Motor Drive for the Flux-Weakening Operation”, IEEE Trans. on Industry Applications, 33, pp. 43-48 (1997).

[5] M. Tursini, A. Scafati, A. Guerriero, R. Petrella, “Extended torque-speed region sensor-less control of interior permanent magnet synchronous motors”, ACEMP'07, pp. 647 - 652 (2007).

[6] M. Cacciato, G. Scarcella, G. Scelba, S.M. Billè, D. Costanzo, A. Cucuccio, “Comparison of Low-Cost-Implementation Sensorless Schemes in Vector Controlled Adjustable Speed Drives”, SPEEDAM '08, Applied Power Electronics Conference and Exposition (2008).

Revision history

Table 43. Document revision history

Date	Revision	Changes
18-Apr-2011	1	Initial release.
24-May-2011	2	Added references for web and confidential distributions of STM32 FOC PMSM SDK v3.0
28-Mar-2012	3	The product range has been expanded from "STM32F103xx or STM32F100xx" to "STM32F103xx/STM32F100xx/STM32F2xx/STM32F4xx". This has impacted several sections, among them the *Introduction*, *Section 10.3: How to create a user project that interacts with the MC API*, *Section 14: Serial communication class overview* and *Section 14.1: Set register frame*.
14-Nov-2012	4	Added “STM32F05xx" to the product range, which has impacted the title and most of the sections. Changed the software library version (from v3.2 to v3.3). Added *Table 1: Applicable products*.
19-Dec-2013	5	Added STM32F30x to the product range, which has impacted the title and most of the sections. Changed the software library version (from v3.3 to v3.4). Added *Table 9: Single-shunt current reading, used resources, single or dual drive, STM32F2xxx/F4xx*. Added *Section 6: Current sensing and protection on embedded PGA* and *Section 7: Overvoltage protection with embedded analog (STM32F3x only)*. Updated *Table 12: File structure*, *Table 13: Project configurations* and *Table 15: MC application preemption priorities*. updated *Figure 59*, *Figure 61*, *Figure 62*, *Figure 90*, *Figure 92*, *Figure 93*, *Figure 94*, *Figure 95*, *Figure 96*, *Figure 99* and *Figure 101*.
20-Jun-2014	6	Updated cover page specifying new features. added on*Section 1* new sensorless specifications, updated list of user interface option on “User project and interface features”. Removed older chapter 9.4: Motor control application project. Added: *Section 8.2*, *Figure 77*, *Figure 79*, point from 7 to 9 in *Section 9.2 on page 96*, *Figure 81*, *Figure 83*, *Figure 84*, *Figure 85*. *Section 12: Light LCD user interface*, *Section 15: Fast serial communication* Updated: – title on *Section 8.1*, *Section 9.1*, *Section 9.2*, – *Figure 75: MC workspace structure*, *Figure 76*, *Figure 78*, *Figure 80*, *Figure 82* – title on *Section 9.5: Full LCD UI project* – title on *Section 11: Full LCD user interface* and *Section 11.1: Running the motor control firmware using the full LCD interface* – *Figure 90*, *Figure 92*, *Figure 93*

Table 43. Document revision history (continued)

Date	Revision	Changes
21-May_2015	7	Updated: – list of features on *Section 1: Motor control library features* – *Figure 59* and *Figure 88* Added: – *Section 4.1* and *Section 4.2* Removed in all document any reference to STM320518-EVAL.
07-Sep-2015	8	Updated: – *Section 3.2*, *Section 5.1*, *Section 9.3*, *Section 9.4*, *Section 9.5* – equation on *Section 4.6* – *Figure 30* Added: – *Section 5.2: Current sampling in three-shunt topology using one A/D converter* – *Section 5.3: Current sampling in three-shunt topology using one A/D converter*

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